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GEOLOGICAL MAGAZINE

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The Growth and Form of Brachiopod Shells

By M. J. S. RUDWICK

ABSTRACT

The form of a brachiopod shell is the product of the rates of growth operating at all points on the valve edges during successive stages of growth. Shell form is analysed here in terms of these rates of growth, the rate at each point being resolved into component rates. If the antero-posterior growth gradients are linear, the shell is rectimarginate; if non-linear, the lateral commissure is "flexed" throughout ontogeny. Localized anomalies in the growth rate may modify either of these basic growth patterns at any stage in ontogeny. They produce *deflections* in the commissure, and these generally produce *deformations* in the valve surfaces (e.g. folds, sulci, costae). Two major varieties of external hinge structure are defined: *strophic* shells have a true hinge line and may also have interareas; *non-strophic* shells have no true hinge line but may have palintropes. The implications of this formal analysis are examined in relation to the systematic description of the shell form.

I. ANALYSIS OF AN ACCRETIONARY STRUCTURE

SINCE the pioneer work on the anatomy and shell-structure of brachiopods in the last century, it has been known that the shells of brachiopods, like those of molluscs, are the products of accretionary growth. But although there have been several general accounts of accretionary growth (Thompson, 1942, pp. 748 ff.; Huxley, 1932, pp. 154 ff.) and at least one discussion of growth and form in brachiopods (Schmidt, 1937, pp. 40 ff.), the significance of this mode of growth seems to have been given little attention by systematic palaeontologists. The purpose of this paper is to outline an analysis of the form of brachiopod shells, and thereby to suggest some ways in which descriptions of the shells can be framed to incorporate the peculiarities of accretionary growth. For the sake of simplicity, the analysis will be illustrated chiefly by hypothetical shell forms. It is confined to features of external morphology.

Owing to the relation between the valve and the mantle-lobe that secretes it (Williams, 1956, pp. 244 ff.), the valve grows in size only by the addition of marginal increments. Once an increment has been added, it remains permanently in that form and position, with the

minor exception that it may later be removed by resorption at the pedicle foramen. The outer surface of the valve therefore preserves immutably the form of the valve edge as it was at all earlier stages of growth. If, by the preservation of growth lines, the phases of its growth are visible, the development of the form of the valve edge and of the valve itself can be reconstructed with complete reliability.

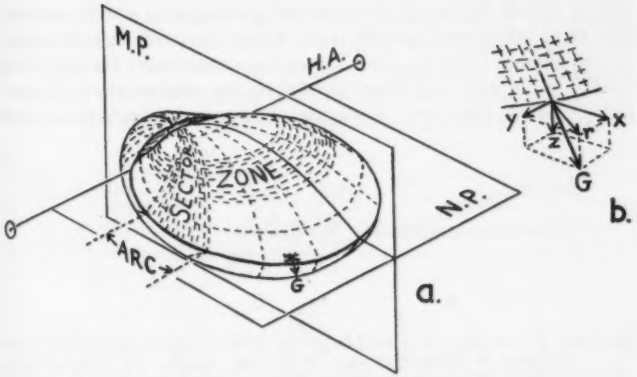
With minor exceptions, the edge of one valve is identical in form with the edge of the other valve: when the valves are closed the valve edges " fit " one another precisely. The development of the form of this common growing edge (the commissure) can therefore be reconstructed with equal facility from the growth lines of either valve; and by combining the evidence of both sets of growth lines the development of the form of the whole shell can be inferred. Thus, as in any accretionary structure, there is a temporal element embodied in the form of the shell.

In principle this is probably widely understood, but in practice brachiopods are frequently described in apparent disregard of these implications of accretionary growth. For example, systematic descriptions rarely include an account of the earlier growth stages of a species, inferred from the growth lines on the adult shells; ontogeny is often treated implicitly as an unknown, unless young specimens are available. Again, it is not uncommon to read such a statement as " the costae die away towards the umbo "; this is of course correct in a formal sense, but is directly contrary to the actual mode of development of the costae. If the temporal factor were incorporated more thoroughly into systematic descriptions, comparisons between different species would be facilitated.

The accretionary mode of growth necessitates the use of two classes of descriptive terms: *momentary* terms, referring to some part or some aspect of the growing edge at any particular *moment* of growth; and *cumulative* terms, referring to structures or tracts of the valve surface formed by some part of the growing edge during a certain *period* of growth. Thus " growth line," " commissure," and " hinge line " are momentary terms; " fold," " sulcus," " interarea," " costa," and most other common descriptive terms, are cumulative. It is convenient to introduce at this point some general terms in both classes (Text-fig. 1*a*). Considering first the whole of the growing edge of a valve, all the shell-material deposited during a certain period of growth may be termed a *zone* of the valve; thus a zone will be a strip of valve surface between any two growth lines or between one growth line and the final valve edge. A zone is a " cumulative " derivative of the whole growing edge. Secondly, any section of the growing edge may be termed an *arc*. The shell material deposited by an arc during the whole growth of the valve may be termed a *sector;*

thus a sector will be a tract of valve surface radiating from the umbo (this use of the term " sector " is an extension of Bancroft's more specialized use; 1928, p. 62). For example, the hinge line is an arc of the valve edge distinguished by its orientation; during the growth of the valve it forms the interarea, which is the corresponding sector. Elements of " concentric " and " radial " ornament are, respectively, distinctive zones and sectors of the valve surface.

The whole valve surface can thus be regarded either (*a*) as a series of



TEXT-FIG. 1.—(*a*) Perspective view of a rectimarginate shell, showing median plane (M.P.), normal plane (N.P.), and hinge axis (H.A.); G represents rate of growth at one point on dorsal valve edge. (*b*) Enlargement of same point on dorsal valve edge, showing G resolved into component growth rates: r, radial; x, anterior; y, lateral; z, vertical.

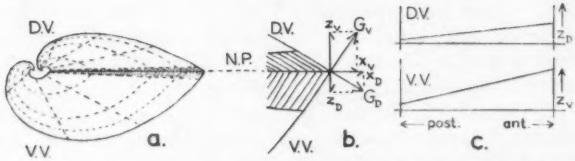
(These abbreviations are used in all the text-figures in this paper.)

zones which were formed by the whole valve edge during successive stages of growth, or (*b*) as a series of sectors which were formed continuously by different arcs of the valve edge.

In principle, the form of any accretionary structure can be fully described in terms of the rates of growth operating at different points on the growing edge during the formation of the structure. Thompson (1942) analysed the growth in terms of the resultant radii of curvature; Huxley (1932) in terms of the ratios between the different dimensions of the structure. Alternatively, the form of the valve can be analysed by resolving the rate of growth at each point on the growing edge, at each moment of growth, into component rates acting in different directions. This kind of analysis is applied here in a simple qualitative manner; it would be cumbersome for biometric studies, but is heuristic for descriptive purposes. It is similar to Owen's (1953) analysis of the

form of lamellibranch shells, but is made simpler by the almost invariable bilateral symmetry of brachiopods. Absolute rates of growth cannot, of course, be inferred from the shell form; but relative rates can be determined with a degree of precision dependent only on the practical methods of measurement employed.

The nature of the component growth rates can be illustrated most simply with reference to a valve of a rectimarginate shell, i.e. a valve in which the growing edge lies in a single plane. This plane will be termed the *normal plane* (Text-fig. 1*a*: N.P.). Then the relative rate of growth (G) at any point on the growing edge can be resolved into three component growth rates, acting mutually at right-angles to one another (Text-fig. 1*b*). The *anterior* component (x) lies in the normal plane and in a plane parallel to the median plane of symmetry, and acts anteriorly. The *lateral* component (y) lies in the normal



TEXT-FIG. 2.—Analysis of a rectimarginate shell of logarithmic spiral form (shown in perspective view in Text-fig. 1 (*a*)). (*a*) Lateral view; a pair of contemporaneous final zones of growth are shaded. (*b*) Enlargement of valve edges on anterior side, showing growth rates operating there during formation of final zones (G_D dorsal, G_V ventral growth rates), resolved into anterior (x_D, x_V) and vertical (z_D, z_V) components. (*c*) Antero-posterior gradients in vertical component, derived by analysis of growth at each point, as in (*b*); vertical scale arbitrary.

plane and acts laterally in a direction perpendicular to the median plane (i.e. parallel to the hinge-axis). The *vertical* component (z) lies in a plane parallel to the median plane, and acts towards the opposite valve, in a direction perpendicular to the normal plane. Any of the components may be termed "negative" if they act in the direction opposite to that stated above. In addition to these three major components, it is convenient to distinguish the resultant of the anterior and lateral components as the *radial* component (r), acting radially in the normal plane.

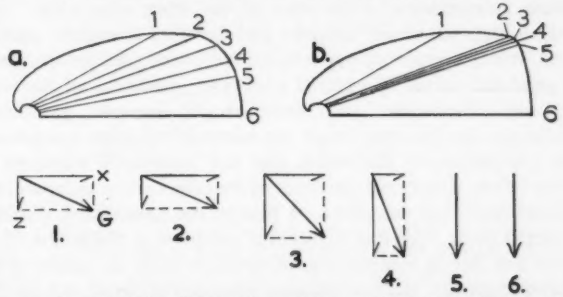
II. The "Linear" Growth Pattern

These component growth rates can be used to interpret the form of any valve. The analysis can be simplified by considering the form of the valve only as it is seen in lateral view. This eliminates the

lateral component—because it acts at right-angles to the median plane—and reduces the variable components to two.

A rectimarginate valve edge is produced if, throughout the growth of the valve, the antero-posterior *gradient* in the vertical component growth rate is *linear*; that is, if the vertical component at successive points around the commissure increases uniformly when traced from the posterior side (i.e. the hinge axis) to the anterior side (Text-fig. 2*c*).

If, at each point on the commissure, the ratio between the vertical and anterior components also remains constant during the growth of the valve, then the valve will have *logarithmic spiral* form (Text-fig. 2*a*). (This is Huxley's term; it is equivalent to Thompson's "equiangular spiral" form, and to Schmidt's *Krümmungs-stetiges Wachstum*.) Successive growth stages of a logarithmic spiral valve



TEXT-FIG. 3.—Analysis of two valves with growth pattern changing during ontogeny. (*a*), (*b*), lateral views. 1–6 represent six successive stages, at which the growth rates were as shown in the vector diagrams. In both cases the zone between stage 5 and stage 6 is a vertical zone.

are identical in form and differ only in absolute size. In such a valve, the relative height and orientation of the interarea, the degree of incurvature and prominence of the beak, and the convexity of the valve as a whole, are all dependent only on the character of the antero-posterior growth gradients in the vertical and anterior components.

If, on the contrary, the ratios between the vertical and anterior components change during ontogeny, the valve will no longer have a logarithmic spiral form. The successive growth stages then differ not only in size but also in form. During the growth of many brachiopod shells there was a directional change in the growth pattern; this is reflected in a directional change of form during ontogeny, as reconstructed from the growth lines. (This growth pattern is Schmidt's *Krümmungs-unstetiges Wachstum*). For example, a progressive increase

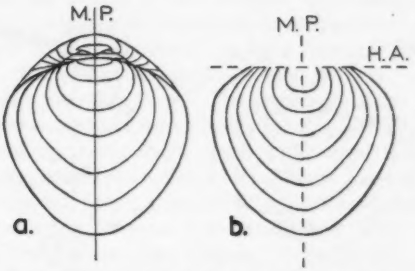
in relative convexity reflects a progressive reduction of the anterior component relative to the vertical component (Text-fig. 3). In some cases the anterior component fell to zero; and if the lateral component fell to zero simultaneously, the vertical component acted alone in the later growth stages to produce a zone which will be termed a *vertical zone* (this is Schmidt's *Hohen-Wachstum*). If the other components were eliminated gradually, the vertical zone is indistinctly limited (Text-fig. 3*a*); if abruptly, the vertical zone is sharply differentiated from the earlier parts of the valve (Text-fig. 3*b*).[1] Similar ontogenetic changes in the posterior growth rates are responsible for changes in the form and orientation of the interarea during growth.

If both valves of a shell are now considered together, it will be clear that the rates of growth on one valve edge cannot vary in complete independence of the rates on the other valve edge. Since the valve edges are closely adjacent and therefore essentially identical in form, only the vertical component can vary in complete independence. This produces valves of unequal convexity, interareas of dissimilar form and orientation, and umbones of unequal prominence (Text-fig. 2). On the other hand, the nature of the other components, which are necessarily correlated (but not necessarily identical) on the two valves, determines the form of the commissure, independently of the convexities of the valves. A plan of the commissure, drawn in the normal plane, therefore depicts the products of the action of the anterior and lateral components, in isolation from the action of the vertical component. Such *commissure plans* can be drawn not only for the final commissure of a shell, but also for selected earlier growth stages of the same shell (by drawing selected growth lines on either valve). If a series of such plans are superimposed (using the median

[1] Schmidt found that in certain species of *Uncinulus* and *Hypothyridina* the shells could be divided into two classes, *Hochformen* with vertical zones developed and *Flachformen* without vertical zones. The absolute size of both kinds of shell varied over the same very wide range. She interpreted these facts as the result of a mode of growth (*Mehrzyklisches Wachstum*) in which the individual had passed through an alternation of periods as a *Flachform* and periods as a *Hochform*; at the end of each *Hochform* period the whole vertical zone had been resorbed before growth on the *Flachform* pattern was resumed. But no such resorption of the external shell-material is known to occur in any other brachiopods. Moreover, it is difficult to believe that after such extensive resorption the new growth would be integrated so accurately with that of the penultimate period that no trace of the intervening *Hochform* period would be preserved on the valve surfaces. It is more probable that there was no resorption during growth; that each individual became a *Hochform* once and for all at a certain stage in ontogeny, by the development of vertical zones; and that this metamorphosis occurred at a widely variable absolute size. On this interpretation, Schmidt's reconstruction of a single ontogenetic series (1937, Abb. 36) is compounded of several separate series, each leading to an "adult" *Hochform* shell of a different size.

plane and hinge-axis as reference lines) the resulting composite plan depicts the ontogenetic changes in the form of the commissure (Text-fig. 4). Commissure plans could be useful in comparing different shells. For example, shells of widely variable convexity might be found to have commissures of very constant form. Or shells of superficially similar form might be found to have developed identical " adult " commissures from very different forms in the earlier growth stages. Such phenomena would be revealed more clearly by the use of commissure plans than by drawings of the whole shell.

All the shell forms discussed above have been rectimarginate. This has been attributed to the existence, continued throughout



TEXT-FIG. 4.—Growth and form of a commissure. (*a*) Dorsal view of a biconvex shell, with several selected growth lines distinguished. (*b*) Commissure plans of the corresponding growth stages.

ontogeny, of linear growth gradients, in the vertical component, between the anterior and posterior sides of the growing edges. The gradients may change in character during ontogeny, but if they remain linear the shell will remain rectimarginate. Growth characterized by persistent linear gradients will be termed the *linear growth pattern.*

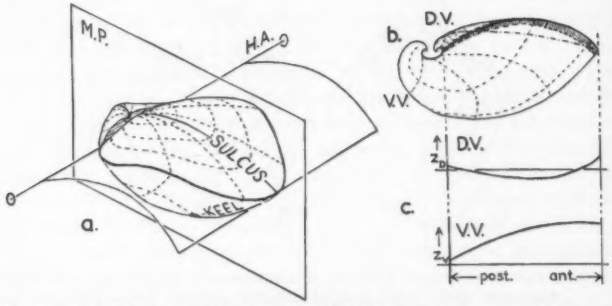
III. The " Non-Linear " Growth Pattern

If the growth gradients are not linear, the commissure will not lie in a single " normal plane ". Growth in which the gradients in the vertical component are persistently non-linear will be termed the *non-linear growth pattern.*

Suppose that the gradient in the vertical component is curved. If this persists throughout the growth of the shell, the valve will have a flexed lateral valve edge. Since the other valve has a valve edge of identical form, its gradient in the vertical component must be curved in the opposite sense from that of the first valve (Text-fig. 5*c*). Thus a shell with correlated non-linear gradients of this simple curved form would have a flexed lateral commissure (Text-fig. 5*b*). According

to the nature of the gradients, the flexure may be conspicuous or inconspicuous, and may be convex either dorsally or ventrally. Shells with lateral flexure are common and widely distributed among the systematic groups, and can be recognized in any published figures in which the shells are shown in strictly lateral view. To give only a few examples, *Dayia navicula* and *Aulacothyris* spp. have a strong flexure, convex dorsally; *Terebratulina retusa* and several species of *Dielasma* (*sensu lato*) have a weak flexure, convex ventrally.

The existence of a flexed lateral commissure does not necessarily have any conspicuous effect on the form of the *surfaces* of the valves, and is therefore commonly overlooked. But if the flexure is strong,



TEXT-FIG. 5.—Growth and form of a shell with lateral flexure. (*a*) Perspective view. (*b*) Lateral view; final zones shaded; the " dot-and-dash " line represents profile of dorsal valve in median plane. (*c*) Antero-posterior gradients in vertical components, showing non-linear character (compare Text-fig. 2 (*c*)).

and the valves are not too highly convex, a very characteristic shell form is produced: one valve has a median *keel* and the other a broad median *sulcus*. If the commissure is flexed dorsally the dorsal valve is sulcate and the ventral valve keeled (Text-fig. 5*a*); and vice versa. Both *Dayia* and *Aulacothyris* show this sulcate-and-keeled form. The same form is conspicuous in the early growth stages of many Rhynchonellids and Terebratulids; its presence is revealed by a keeled ventral umbo and a sulcate dorsal umbo. Buckman (1918, p. 16) termed this the " *Norella* " or " inverted " stage; but it will be suggested in a later section of this paper (p. 17) that it does not in fact represent a stage comparable with his " everted " and other stages.

If the valves are slightly more convex, or the lateral flexure slightly weaker, the sulcate-and-keeled shell form is not found. The median sulcus is replaced by a flat or gently convex area, and the median keel is less conspicuous (e.g. *Terebratulina retusa*). If this shell form

is conspicuous in the early growth stages, the ventral umbo is keeled but the dorsal umbo is not sulcate. This was noted by Buckman, but he attributed the loss of the sulcate umbo to " precedentive palingenesis " (1918, p. 16). In fact, only variations in the convexity of the dorsal valve or in the degree of lateral flexure would be required for the repeated acquisition—or loss—of the " *Norella* stage ".

If the lateral flexure is still weaker, the form of the valve surfaces is not affected in any conspicuous way; and the existence of the flexure can only be perceived in strictly lateral views of the shell (e.g. *Dielasma* spp.).

It seems to be characteristic of all these " non-linear " shells that the form of the lateral flexure remains approximately constant (relative to the size of the shell) throughout ontogeny; in other words, the character of the non-linear gradients remains approximately unchanged. Rectimarginate shells do not become " non-linear " during ontogeny, nor vice versa. The degree of lateral flexure may therefore be a character of systematic significance.

But like rectimarginate shells, shells with lateral flexure may or may not have logarithmic spiral form: though the gradient in the vertical component keeps a constant non-linear character during ontogeny, the ratios between the vertical and other components may remain constant or may change. For example, the relative convexities of the valves may increase during ontogeny, and vertical zones may be formed, while the lateral flexure remains unaltered.

In reality the non-linear gradients are probably never as simple as in the example shown in Text-fig. 5. Generally the lateral commissure is not flexed in such a simple curve. For example, in *Aulacothyris resupinata* the flexure is quite strongly sigmoid; this was apparently produced by non-linear gradients of sigmoid form. Nevertheless, the flexure remained essentially similar throughout ontogeny, and such shells can properly be included with more simple forms as products of a non-linear growth pattern.

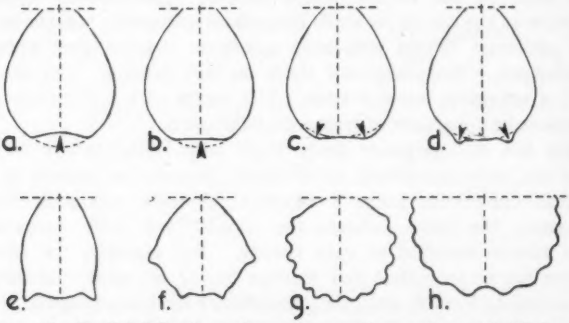
IV. Deflections and Deformations

In a very common type of brachiopod shell, most of the commissure is rectimarginate, but a fairly sharply defined median anterior arc is deflected out of the normal plane (this makes the commissure either " sulcate " or " uniplicate ", on Buckman's terminology); generally this is associated with a median fold in one valve and a median sulcus on the other (Text-fig. 9*a*). This kind of commissure could be interpreted as the product of markedly non-linear gradients in the vertical component (Text-fig. 9*b*); but it is simpler to regard it as the product of a *localized anomaly* in the vertical component, superimposed on a growth pattern of linear gradients (this follows

the lines of Huxley's analysis of similar cases in other accretionary structures; 1932, p. 161).

The effect of an anomaly on the form of the commissure will be termed a *deflection* of the commissure. Under appropriate conditions, the continued existence of a deflection during the growth of the shell may give rise to corresponding *deformations* in the valve surfaces (e.g. a fold on one valve and a sulcus on the other). Thus deflections are " momentary " features; deformations are the corresponding " cumulative " features.

The nature of a deflection can be analysed in terms of the anomalies responsible for its formation. Most deflections are found on analysis



TEXT-FIG. 6.—Radial deflections, shown on commissure plans. (*a*)–(*d*) A series of hypothetical commissures; black pointers indicate interpretations of position and direction of deflections; (*b*) and (*c*) show alternative interpretations of the same commissure. (*e*) *Digonella digona.* (*f*) " *Spirigera* " *trigonella.* (*g*) " *S.*" *multicostata.* (*h*) *Argyrotheca cuneata.*

to be due to a localized anomaly which is partly " radial " and partly " vertical " in character. But it is usual for the anomaly in one component to be more conspicuous than that in the other. Deflections can therefore be divided into two main classes, radial deflections and vertical deflections; but this classification is merely one of convenience.

(i) *Radial deflections* are due to anomalies in which an anomalous radial component is dominant. Since, by definition, no anomaly in the radial component can affect the rectimarginate character of the commissure, radial deflections can be depicted conveniently on commissure plans (Text-fig. 6). But their description and classification presents some difficulty; for to term any arc " deflected " or " anomalous " involves a prior definition of the " normal " or " undeflected " shape of the commissure, and this definition is bound to include a purely arbitrary element. For example, the commissure shown in Text-fig. 6*b* and *c* can be interpreted as showing either

a median negative deflection (6*b*) or paired positive deflections (6*c*); the difference depends only on the prior choice of a smoothly-rounded form to be regarded as " normal ". In more extreme developments of the same type of commissure (Text-fig. 6*a* and *d*), the deflections may be sufficiently well defined to make one interpretation clearly preferable to the other. Nevertheless there remains an arbitrary element in the description of all radial deflections; but this does not lessen the value, for comparative purposes, of drawings of such commissures.

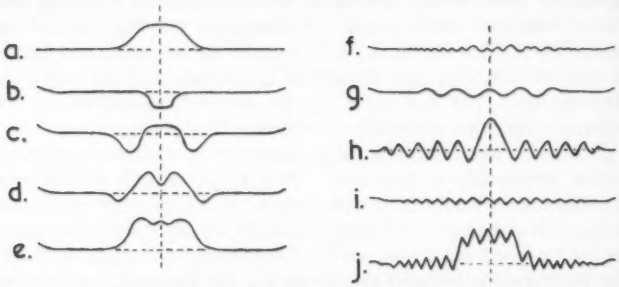
Three classes of radial deflections may be distinguished. *Median* deflections occur singly, centred on the median plane (Text-fig. 6*a*). *Paired* deflections occur in pairs, symmetrically on either side of the median plane (Text-fig. 6*d*, *e*, *f*). If the pairs are numerous and similar to one another, they can be termed collectively a *serial* deflection (Text-fig. 6*h*); and this name can be extended to include sets of deflections which are not strictly symmetrical (Text-fig. 6*g*).

(ii) *Vertical deflections* are due to anomalies in which an anomalous vertical component is dominant. They therefore shift certain arcs of the commissure out of the normal plane. By a convention analogous to that used in diagrams of ammonite sutures, a brachiopod commissure can be " opened out " into what will be termed a *commissure trace*. The normal plane becomes the datum line for the trace, and vertical deflections appear as deflections from that line (Text-fig. 7). For depicting the form of commissures with vertical deflections, this device combines the aspects usually shown in anterior and lateral views of the shell, but eliminates the distortions due to the curvature of the commissure.[1]

The description of vertical deflections presents less difficulty than that of radial deflections; for in most cases part of the commissure is clearly undeflected and still lies in the normal plane, and this provides an objective datum from which to describe the direction and extent of the deflections. *Median* vertical deflections (Text-fig. 7*a*, *b*) occur singly, centred on the median plane, and directed either dorsally or ventrally: these are respectively, Buckman's " uniplicate " and " sulcate " types of plication (1918, p. 83). *Paired* deflections occur in pairs, symmetrically on either side of the median plane, and directed either dorsally or ventrally; paired deflections, either alone or in

[1] In practice, a commissure trace can be obtained (*a*) by rotating the shell in the normal plane like a wheel over a flat surface of plasticine, and then drawing the resulting impression by camera lucida; or (*b*) by drawing short arcs of the commissure separately, rotating the specimen arc by arc so that the arc being drawn is always perpendicular to the line of sight (to avoid distortion), and finally piecing the several drawings together. Method (*b*) is more cumbersome than (*a*), but must be used when no clear plasticine impression can be obtained, and for drawing commissure traces from growth lines on the valve surfaces.

conjunction with median deflections (Text-fig. 7*c*, *d*), form the remainder of Buckman's types of plication (except " multiplicate ", " ligate ", and " pliciligate "), though it should be noted that many varieties of plication do not fall readily into any of his categories (e.g. Text-fig. 7*e*). If the paired deflections are numerous and similar, they can be termed collectively a symmetrical *serial* deflection (Text-fig. 7*g*); and this name can be extended to include asymmetrical sets of deflections (Buckman's " multiplicate " type belongs here; see Text-fig. 7*f*, *i*). Even if a serial deflection affects almost the whole of the commissure, there is usually a short undeflected arc posteriorly, which indicates



TEXT-FIG. 7.—Vertical deflections, shown on commissure traces (dorsal side above). (*a*) *Martinia glaber*. (*b*) *Terebratella cuneata*. (*c*) *Composita ambigua*. (*d*) *Sphaeroidithyris eudesi*. (*e*) *S. sphaeroidalis* var. (*f*) *Plectothyris fimbria*. (*g*) *Atrypina barrandei*. (*h*) *Spiriferina münsteri*. (*i*) *Globirhynchia subobsoleta*, juv. (*j*) *G. subobsoleta*, " adult."

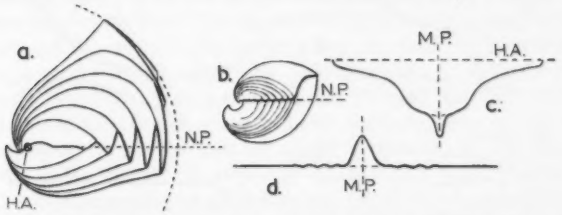
that the deflection should be regarded as an alternation of dorsal and ventral deflections (see Text-fig. 7*h*).

A median deflection may be combined with a serial deflection in the same shell. In the commissure shown in Text-fig. 7*h*, the median deflection arises during ontogeny from the enlargement of the median member of the serial deflection; in other words, the median and the serial deflections are ontogenetically related. But in other shells a median and a serial deflection are co-existent but ontogenetically independent: they appeared at different stages and developed at different rates (Text-fig. 7*i*, *j*). Buckman gave implicit recognition to this fact, for he used the order of appearance of plicae (i.e. a serial deflection) and " trilobation " (i.e. a median deflection) as a generic character (1918, pp. 23–6).

(iii) *Composite deflections* are those in which anomalous radial and vertical components are both conspicuously responsible for the form of the deflection.

If any of the vertical deflections described above are developed

to considerable amplitude, it becomes clear that in fact the responsible anomaly is composite in character. This is seen most clearly on the flanks of strong vertical deflections—either median or serial—in the anterior arc. The commissure is not deflected there in a line perpendicular to the normal plane, as it would be if the anomaly were purely vertical; it is deflected into an arc centred on the hinge axis (Text-figs. 8*a*, 11*b*). This can only be the result of an accurate balance between the vertical and radial elements of the anomaly, a balance correlated with the distance of each deflected point from the normal plane and from the hinge axis. It is thus a property of such deflections that every point on the commissure, however far it is



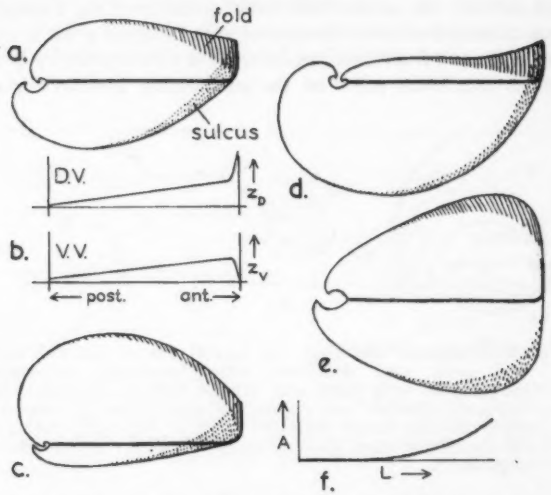
TEXT-FIG. 8.—Composite deflections. (*a*) Lateral view of shell with median and serial axial deflections (*Rhynchonelloidea subangulata*). (*b*)–(*d*) Shell with radial and vertical median deflections superimposed ("*Spirifer*" *triangularis*): (*b*) lateral view; (*c*) commissure plan, showing radial deflection (vertical deflection eliminated); (*d*) commissure trace, showing vertical deflection (radial deflection eliminated).

deflected out of the normal plane, retains its "normal" distance from the hinge axis. This can be demonstrated by formally "rotating" the deflected arcs, around the hinge axis, back into the normal plane;[1] in most cases it is then found that the reconstructed commissure plan is smooth and regular; this would not be so if the deflections were purely vertical. This special type of composite deflection will be termed an *axial* deflection. Probably most of the deflections classed above as "vertical" are in fact axial; but this can only be demonstrated conclusively in shells in which the deflections are strongly developed.

Axial deflections are probably the commonest type of composite deflection; but other varieties occur. In the example figured here (Text-fig. 8*b–d*) a composite median deflection is compounded of a very sharp positive radial deflection and a rather broader dorsal vertical deflection.

[1] In practice, this can be done by drawing partial commissure plans of the deflected and undeflected arcs separately, and then superimposing the drawings in the same orientation relative to the median plane and the hinge axis.

The *deformations* produced by all these deflections are probably more generally familiar than the deflections themselves. This is because systematic descriptions almost invariably mention only the deformations: Buckman's work of 1918 remains one of the very few extensive works in which the form of the commissure is consistently described. Yet the perception of similarities and differences between one shell



TEXT-FIG. 9.—Deformations produced on four different shell forms by the same type of median vertical deflection. Rate of development of deflection shown in curve (*f*) (A, amplitude of deflection ; L, length of commissure from hinge axis to anterior side). Dorsal fold and ventral sulcus shown by shading on lateral view of each shell (the sulcus, as it would appear if shell were transparent). (*b*) growth gradients for shell (*a*), showing anomalies in vertical component.

and another—which is of course the foundation for any systematic work—is made more difficult by this concentration on the character of the valve surfaces. For the effect of a deflection on the form of the valve surfaces does not depend solely on the character of the deflection; its expression on the valve surfaces is modified significantly by the " overall " convexities of the valves, i.e. by the nature of the growth pattern on which the localized anomaly is superimposed. Thus, deformations are, in a sense, " composite " in origin; they are the products of two independently variable factors, the nature of the deflection and the nature of the " overall " growth pattern. Identical

deflections, if they modify different " overall " growth patterns, will produce different effects on the valve surfaces. Conversely, similar deformations may be due to different deflections. If it is only the deformations that are studied and described, a basic similarity will be overlooked in the first case, and a fortuitous resemblance will be stressed in the second.

This can be illustrated by the very simple example of a rectimarginate shell in which a dorsal median vertical deflection developed at an increasing rate in the later growth stages (Text-fig. 9*f*). (*a*) If the valves are of equal and moderate convexity, the development of this deflection will produce a median fold in the dorsal valve and a median sulcus in the ventral valve; both will be increasingly accentuated towards the anterior edge of the shell (Text-fig. 9*a*). (*b*) If the dorsal valve is highly convex and the ventral valve nearly plane, the fold will be low and inconspicuous but the sulcus will be deeper than in the first case (Text-fig. 9*c*). (*c*) If the convexities are reversed, the fold will be more prominent but the sulcus will be shallower than in the first case (Text-fig. 9*d*). The sigmoid profile of the fold in this case is likewise dependent on the convexity of the dorsal valve relative to the rate of development of the deflection. (*d*) If ti.e relative convexity of both valves increased during growth until finally vertical zones were formed, the fold and sulcus will be increasingly prominent away from the umbones, but only up to a certain point; nearer the anterior edge they will become less prominent and finally, on the vertical zones, will have no surface expression at all (Text-fig. 9*e*). Instead there will be a " linguiform extension " on the dorsal valve, in the same plane as the rest of the vertical zones. Hence one and the same type of deflection can produce a variety of features on the valve surfaces, according to the convexities of the valves.

This is a very simple example. With more complex deflections the range of variety possible in the deformations is even greater. However, it is only possible to add here a description of some of the simpler effects of *serial* deflections. On a biconvex shell, a serial radial deflection will produce a series of radial costae on each valve. Each costa on one valve will correspond in position to a costa on the other valve; this is Buckman's (1907) " opposite " type of costation. For any particular deflection, the " strength " or prominence of the costae will be greatest on a highly convex valve; on a perfectly plane valve there will be no costae at all. On an unequally biconvex shell, the costae will be more prominent on the more convex valve. A serial vertical deflection will also generally produce costae on both valves. But in this case each costa on one valve will correspond in position to the furrow between two costae on the other: this is Buckman's " alternate " type of costation. For any particular deflection, the costae

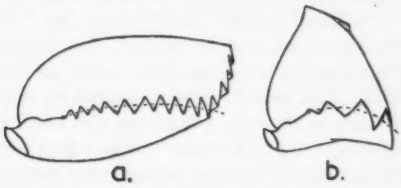
will be more prominent on a gently convex valve than on a highly convex valve; they will be most prominent on a plane valve and completely absent on a vertical zone. Hence, if the valves increase in relative convexity during ontogeny, with the final formation of vertical zones, and if the deflection is steadily increasing in amplitude at the same time, then the costae will become increasingly prominent when traced away from the umbo, but only up to a certain point, beyond which they will gradually die away.

If a serial deflection is combined with a median deflection the character of the deformations is less simple to analyse. The effects of the two deflections are naturally superimposed on one another. Hence, if both deflections are vertical, and the median deflection is dorsal (e.g. most Mesozoic Rhynchonellids) the costae are necessarily more prominent on the fold than on the rest of the dorsal valve, and less prominent in the sulcus than on the rest of the ventral valve. Descriptions of this kind of shell sometines include remarkable

TEXT-FIG. 10.—Anterior views of three variants of a shell with median and serial vertical deflections; showing relation of costae on fold to those in sulcus.

statements, such as " There are three costae in the sulcus and four on the fold ". But since both sets of costae are the cumulative products of the same arc of the serially deflected commissure, it is inevitable that there should always be one more costa on the fold than in the sulcus (Text-fig. 10). The statement is therefore tautologous. Similarly, if the formal and ontogenetic independence of the median and serial deflections is not recognized, the number and spacing of the costae, and the width of the fold and sulcus, may be dismissed as being too variable to be of any value in systematic descriptions. For these characters are generally described in combination (i.e. as the number of costae on the fold or in the sulcus); and by this method the constancy of one is liable to be masked by the variability of the other. For example, measurements on species of *Globirhynchia* suggest that, relative to the size of each shell, the width of the median deflection is highly variable but the " wave-length " of the serial deflection is very constant (Text-fig. 7*j*). The latter character would be useful for systematic discrimination, but its constancy would be overlooked if it were not separated formally from the more variable character which accompanies it.

All these deflections and deformations have been described here as modifications of a rectimarginate shell, i.e. of a linear growth pattern. But any of them may also modify shells with a flexed lateral commissure, i.e. shells with a non-linear growth pattern. This produces very complex shell forms. It has been pointed out (p. 8) that Buckman's " inverted " or " *Norella* " stage, as seen on the umbones of some shells, represents non-linear growth. A study of the growth lines of some of the species cited by him (e.g. *Sphenorhynchia plicatella*, *Homoeorhynchia cynocephala*) shows that there is no truly rectimarginate stage between the " inverted " and the " everted " stage, i.e. between the early stage with a keeled ventral valve and sulcate dorsal valve, and the later stage



TEXT-FIG. 11.—Lateral views of *Sphenorhynchia plicatella* (*a*) and *Homoeorhynchia cynocephala* (*b*), showing dorsal flexure of lateral commissure throughout ontogeny. One early growth line is indicated (on ventral umbo) to show lateral flexure at that stage; final commissure also flexed, but modified by development of median and serial axial deflections.

with a sulcate ventral valve and a folded dorsal valve. The " *Norella* " stage did not undergo " eversion " into the " *Rhynchonella* " stage. Instead, it is clear that the later " uniplication " was *superimposed* on a pre-existing " *Norella* " type of commissure; i.e. a dorsal median vertical deflection was superimposed on a non-linear growth pattern. The non-linear growth pattern persisted throughout the growth of the shell; its existence in the later growth stages is masked by the development of the median deflection, but is betrayed by a lateral commissure which (after formally eliminating the additional serial deflection) can be seen to have remained flexed at every growth stage (Text-fig. 11).

This interpretation of the form of these complex shells emphasizes the reality of the distinction between the non-linear growth pattern on the one hand, and localized anomalies on the other. Non-linear growth produces a flexed lateral commissure, which seems to remain essentially unchanged in character (relative to the size of the shell) throughout ontogeny. Localized anomalies may be superimposed on either the non-linear or the linear growth pattern; they produce deflections, which are generally absent in the early growth stages

and almost invariably change in character and develop with increasing intensity (relative to the size of the shell) during ontogeny.

V. The Growth and Form of the Hinge

Since the term " hinge line " is generally used for a morphological feature of the shell, it is necessary to distinguish the *hinge axis* as the line in space about which the valves rotate as they open and shut (Text-fig. 1*a*). It is in this sense that the term has been used in the earlier sections of this paper. The relation between the hinge axis and the morphological hinge of the shell has been the source of much terminological confusion. The terms " cardinal area " or " interarea ", " palintrope ", "cardinal margin ", and " hinge line " have been used in several different senses, and not always even clearly defined (for summaries of some of the meanings of the terms, see Thomson, 1927, and Cloud, 1942). The position can be clarified by emphasizing that two essentially different growth patterns in the cardinal region give rise to two different forms of external " hinge " (this discussion is not concerned with the role of the internal teeth and sockets as elements of the articulatory mechanism). This distinction seems to have been recognized, at least in part, by several authors, but does not appear to have been defined or analysed in detail. As one of the very few clear-cut morphological distinctions in brachiopods, it has played a curiously small part in discussions of systematics.

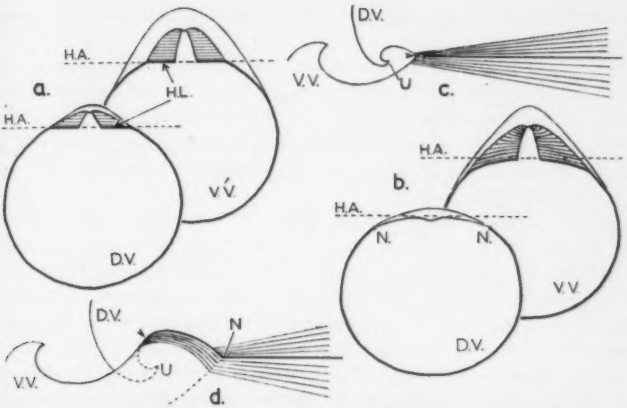
There are two primary distinctions between the two growth patterns. (i) Either some arc of the growing edge of each valve lies exactly in the line of the hinge axis, or no arc has this exact orientation. (ii) Either the growing edges of the valves are exactly identical in extent, or there are certain arcs of one growing edge which have no equivalents on the other growing edge.

In the first case, then, the growing edges are identical in extent, and certain arcs on each edge lie exactly in the line of the hinge axis (Text-fig. 12*a*). These arcs constitute a true hinge line. This, in a strict sense, acts as the " pivot " of the articulation; it is the " axle " about which the valves rotate. It is therefore appropriate to term shells of this type *strophic*. They correspond to Cloud's " straight-hinged " shells; but his term is not ideal, for it is mechanically impossible for a true hinge line to be otherwise than straight. The term hinge line should therefore be restricted in this functional sense, and not used, as it was by Thomson (1927, p. 52) as a synonym of " cardinal margin ".

As a strophic shell grows, the continued existence of the hinge line produces the corresponding sectors on both valves (Text-fig. 12*c*). Following Cloud (1942, p. 13), these should be termed " interareas "

or "cardinal areas". The length of the hinge line, relative to the breadth of the whole shell, is highly variable (e.g. very long in *Mucrospirifer* and short in *Brachythyris*); but in every case some arc of the growing edges—however short—lies exactly in the line of the hinge axis. Again, if the rate of growth on the hinge line was very slow, there are no distinct interareas (e.g. Productids); but nevertheless it is clear that the posterior arcs form a true hinge line.

In the second type of hinge structure, no arc of either growing



TEXT-FIG. 12.—Growth and form of strophic (*a*), (*c*), and non-strophic (*b*), (*d*) hinges. (*a*), (*b*) internal views of valves; growing edges shown as thick lines; interareas and palintropes shaded. (*c*), (*d*) enlargements of hinge region, in lateral view, showing relation of increments of growth (five are shown on each valve) to hinge axis (shown by black pointer). U, dorsal umbo; N, nick point.

edge lies exactly in the line of the hinge axis, and the growing edges themselves are dissimilar in extent (Text-fig. 12*b*). There is therefore no morphological hinge line to act as the pivot or axle of the articulation, and the shells of this class can be termed *non-strophic*. The posterior arcs (i.e. the "cardinal margin") may lie very close to the hinge axis, but as they do not lie precisely in line with it, they cannot function as a true hinge line. "Palintropes" (Cloud, 1948, p. 20–1), which may be formed cumulatively by the growth of these arcs, are therefore fundamentally different from interareas. The difference between them can generally be recognized without difficulty by noting the orientation of the growth lines on them (see Text-fig. 12*a*, *b*).

In principle it would seem possible for such shells to have, in every other respect, the same growth pattern as any strophic shell; for

example, they could be identical in growth gradients—and hence in lateral profile—with either of the shells shown in Text-figs. 2 and 5. But in fact all non-strophic shells conform to a single distinctive pattern. The dorsal umbo is always relatively strongly incurved, is tucked into the delthyrium, and is therefore hidden from external view. Consequently the ventral umbo is relatively conspicuous (Text-fig. 13), and this has caused non-strophic shells to be termed "rostrate" (e.g. Cloud seems to use the term as the opposite of "straight-hinged"); but the use of the same term to include any shell with a prominent umbo (e.g. Thomson, 1927) suggests that it would be better to abandon it.

The growing edges of the valves are not identical. Growth on the dorsal valve is "hemiperipheral": it does not extend as far back as the hinge axis. The most posterior arcs of the ventral growing edge have no equivalents on the dorsal growing edge. The points at which the dorsal growing edge terminates will be termed the *nick points* (Text-fig. 12*b*, *d*: N.).

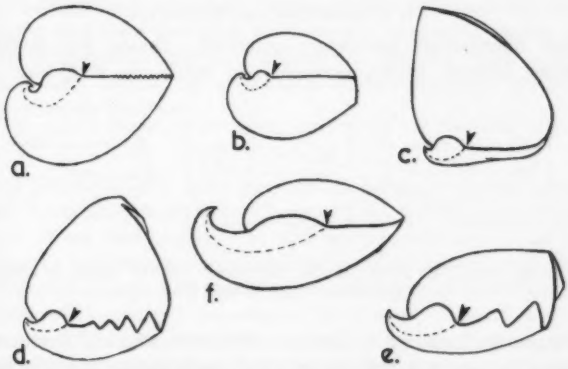
Since all elements of "radial ornament" (except some types of striae and costellae) are produced by the "co-operative" action of localized anomalies in the growth rates on both growing edges, it is impossible for such ornament to be formed on these posterior arcs. Consequently, the corresponding sectors, which are approximately co-extensive with the palintropes, are invariably smooth except for growth lines and striae. This appears to be the causal explanation of the absence of ornament on palintropes, a phenomenon which has been noted by several authors.

The growth rate on the dorsal valve at the nick points is greater than zero. The dorsal valve edge between the nick point and the umbo therefore has a roughly logarithmic spiral form, representing the locus of the nick point itself during the growth of the valve (Text-fig. 12*d*: U N.). If the two valve edges are to be in close contact with one another between the nick point and the hinge axis, as they are on the rest of the commissure, the ventral growing edge on this arc must be deflected to "fit" the logarithmic spiral in the dorsal valve edge (Text-fig. 12*d*). This is achieved by a localized anomaly in the vertical component growth rate on the ventral growing edge; but unlike a true deflection there is no corresponding anomaly in the dorsal growing edge.

The non-strophic growth pattern can thus be recognized not only by the lack of a true hinge line, but also by the presence of a dorsally directed deflection in the commissure near the hinge axis. On many shells this deflection is conspicuous (Text-fig. 13); it will be termed the *non-strophic deflection*. The prominence of the deflection depends, however, on the magnitude of the dorsal growth rate at the nick point.

If this is slight, the deflection is inconspicuous. On many Terebratuloids, for example, the nick point is close to the hinge axis and the dorsal growth rate there was very slow; on such shells the presence of a non-strophic deflection—and indeed the dissimilarity of the growing edges—may be impossible to detect unless the specimen is exceptionally well preserved. But even if this is so, the non-strophic character of the shell is clearly revealed by the other criterion, the absence of a true hinge line.

It is difficult to conceive any single morphological series which



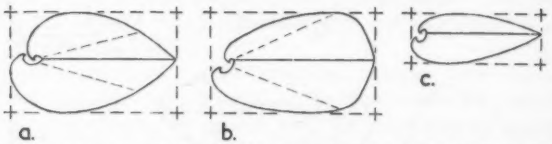
TEXT-FIG. 13.—Lateral views of non-strophic shells, showing non-strophic deflection. Black pointers indicate nick points. (*a*) *Conchidium knighti*. (*b*) *Gypidula galeata*. (*c*) *Pugnax acuminatus*. (*d*) *Tetrarhynchia tetrahedra*. (*e*) *Rhynchotreta angulata*. (*f*) *Uncites gryphus*.

could link the non-strophic to the strophic hinge pattern, and the distinction between them must be regarded as an important feature of formal morphology. The reason for its neglect in systematics is probably to be found in the confusion over the meaning of the terms "hinge line", "interarea", and "palintrope", which has effectively masked the distinction. A cursory survey of some of the commoner or more representative genera in the major groups shows that strophic and non-strophic shells have an interesting distribution (the classification here follows Muir-Wood's (1955) summary). Apparently all members of the Orthoidea, Dalmanelloidea, Clitambonitoidea, Triplesioidea, Strophomenoidea, Productoidea, and Chonetoidea are strophic; and all members of the Rhynchonelloidea and Atrypoidea are non-strophic. But whereas most of the Syntrophioidea are strophic, *Porambonites* is not. Most of the Pentameroidea are non-strophic, but the Stricklandidae are strophic. Most of the Spiriferoidea are

strophic, but the Athyracea (except the Koninckinidae) are not. Most of the Terebratuloidea are non-strophic, but the Stringocephalidae are strophic. Most of the Terebratelloidea are also non-strophic, but the Megathyridae and a few other shells (e.g. *Magas pumilus*, *Trigonosemus elegans*) are strophic. This list is not intended to be definitive, and may be inaccurate in several details. It merely gives a provisional indication of the approximate distribution of the two forms of hinge. But even as it stands, the list suggests that the distinction deserves greater attention from systematists.

VI. Parameters for Statistics

The dimensional parameters commonly chosen for statistical analyses (overall length, breadth, and height of shell) are very



Text-fig. 14.—Two shells (*a*), (*b*), with same ratio of height to length. (*c*) young stage of shell (*b*).

unsuitable for the purpose. Owing to the consequences of accretionary growth, the use of a ratio between two such parameters may unite unrelated shells and separate related ones. This may be illustrated by a very simple example. Consider the ratio between height and length. A shell of constant moderate convexity (Text-fig. 14*a*) and a shell which changed during ontogeny from gently convex to highly convex growth (Text-fig. 14*b*) could both have precisely the same ratio, and in statistical treatment would be regarded as identical in this character. Suppose that these two shells were typical of two variable species occurring in a mixed assemblage. Then the use of the ratio between height and length would not only fail to discriminate between the members of the two species; it would also separate the young individuals of the second species (Text-fig. 14*c*) from the corresponding adult individuals. If the assemblage contained an appreciable proportion of young specimens, the statistical analysis would therefore reveal a bimodal distribution; and unless the statistics had been founded on, and preceded by, a thorough qualitative study of the shell forms, this bimodal distribution would certainly be taken to reveal the presence of two species differing in the ratio of height to length. But in fact one mode would represent all the specimens of the first species and the adults of the second, while the other mode would

represent only the young specimens of the second species. This is a very simple example; for more complex shell forms the possibilities of error and confusion are greatly increased.

The use of statistics based on these parameters does not therefore represent an advance of knowledge about the shells. On the contrary, it is liable to represent a loss of knowledge. For on any shell the magnitude of each parameter is the cumulative product of all the rates of growth which have operated at every successive stage in the growth of the shell; any particular magnitude may have been produced by any of an infinite number of different growth patterns. The parameters therefore represent such a high degree of abstraction from the actual observed shell form that they are extremely misleading, unless they merely supplement a qualitative description. Statistics based on them cannot avoid having an appearance of morphological precision, which is largely spurious.

VII. Conclusions

The purpose of this paper has been to isolate by formal analysis some of the different elements involved in the growth of brachiopod shells. It has been suggested at several points that the use of such an analysis may serve to reveal similarities and differences which would be less easily recognized from more conventional modes of description. In this way, it is hoped that some of the concepts outlined here may prove useful in the systematic description of brachiopods. The terminology, on the other hand, has been developed merely to facilitate the analysis, and would not necessarily be appropriate for systematic purposes.

In order to illustrate each factor in turn without complications, the analysis has been concerned chiefly with simple hypothetical shells. Most actual shells are the products of extremely complex interactions between many or all of the factors distinguished here. Deflections of different types, superimposed on one another and developing at different rates during ontogeny, modify a highly variable "overall" growth pattern, which may be based either on linear or on non-linear gradients in the rates of growth; and all this may occur in conjunction with either the strophic or the non-strophic type of hinge. During ontogeny, the cumulative effects of all these factors produces the subtly complex shell forms of familiar brachiopods. It is facile to suppose that such crude parameters as overall length, breadth, and height can express these shell forms adequately for statistical purposes.

Since the shell is the cumulative product of these varied factors, its form should be described "dynamically", i.e. in such a way that the description emphasizes the sequence of stages which brought the

shell to its final form; and it should be analysed into its formally independent components. If this is done, it may be found that some of the " external features " possess a constancy and a systematic significance which is often assumed to belong only to the " internal features " of the shell.

VIII. Acknowledgments

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Pseudomigmatites in the Abitau Lake Area, District of Mackenzie, Northwest Territories, Canada

By W. T. Harry

Abstract

The Abitau Lake area, N.W.T., chiefly consists of medium-to-coarse-grained quartzo-feldspathic gneisses. Many of these are granoblastic, presenting little or no microscopic evidence of deformation. Others are highly tectonized and foliated varieties that sometimes form pseudomigmatites easily mistaken in the field for true migmatites formed by *lit-par-lit* injection of pink granite into more basic grey gneiss. The last, however, are found after detailed examination to be granitic rocks that owe their misleading appearance and distinctive fabric to deformation during isochemical amphibolite facies metamorphism. Surprisingly they are not mylonites. Their fabric, like that of the other foliated gneisses is dominated by the parallelism of dark minerals and elongated quartz crystals. It resembles that of typical European granulites and often seems largely due to compression acting in a direction normal to the foliation plane with little or no transport in that plane. Tectonization did not promote the formation of myrmekite or microperthite but may have assisted to some extent the production of epidote from hornblende in certain specimens.

Introduction

North-east of Lake Athabaska in the Canadian Shield between lats. 60 and 61 N. and longs. 106 and 108 W. the Abitau Lake map area (Hoadley, 1955) largely consists of pink granitic and grey granodioritic-dioritic gneisses with a regional north-east strike. Many, perhaps the majority, of these rocks are granoblastic, containing equant quartz and feldspar. Some are mylonites. A large number are characterized by a fabric like that of typical Finnish granulites and it is these that are the prime concern of this paper.

Migmatites, in the following account, are gneissic rocks in which two components of different age and composition can be megascopically discerned. They can be of diverse origin. Pseudomigmatites are gneisses of migmatitic *aspect only*, due to deformation during isochemical metamorphism of one homogeneous parent. The term has been used in a somewhat similar sense by Chapman (1942).

Granoblastic Gneisses

The granoblastic gneisses are chiefly granitic and granodioritic-dioritic rocks in which quartz and feldspar (av. grain size 0·5–1 mm.) form equant crystals with slightly irregular but not intricately sutured outline. They present little or no microscopic evidence of deformation. Lenticular crystals are rare ; quartz shows only slight strain effects and lacks Boehm lamellae. Mica plates are not deformed ; plagioclase twin lamellae are generally straight, sometimes slightly bent. In

many hand-specimens no obvious foliation is present. Field exposures, however, commonly show a vague foliation due to slight concentration of dark minerals sometimes emphasized by pegmatitic folia and alternate granitic, granodioritic, and more basic layers. This structure, which is often steeply inclined and folded, is deflected by occasional small pre- or para-crystalline shear planes.

The granitic gneisses contain abundant quartz, microcline, and oligoclase or andesine. Often, but not always, the microcline is well-twinned and slightly microperthitic. Myrmekite is occasionally present, but is absent from most plagioclase-microcline junctions. Small quantities of biotite and sometimes green hornblende occur. Common accessories are sphene, zircon, apatite, and iron ore. Muscovite forms occasional ragged areas. Enstatite, as apparently unstable relicts in quartz, is present in one specimen of pegmatitic granitic gneiss migmatizing granodioritic gneiss.

The granodioritic and dioritic gneisses are essentially composed of quartz, plagioclase, biotite, and often also deep-green hornblende. The feldspar is andesine or basic oligoclase, unzoned, and generally fresh with albite twinning ; inclusions are rare. Biotite, olive- or reddish-brown, rarely chloritized, contains zircon inclusions surrounded by pleochroic haloes. Garnet, common as clear crystals up to about 1 cm. broad, becomes unstable in specimens migmatized by granitic gneiss when it is sometimes replaced by decussate sheaves of biotite or white mica. In the field permeation and veining of garnetiferous granodioritic-dioritic gneiss by pink granitic gneiss can be seen to be accompanied by the disappearance of garnet.

Microcline sometimes forms antiperthitic patches in plagioclase and irregular interstitial areas between quartz and feldspar in the granodioritic-dioritic gneisses. Sphene, apatite, iron ore and zircon (often metamict) are common accessories. Hypersthene is moderately plentiful in one coarse grey foliated specimen essentially composed of andesine and quartz with a little microcline, garnet, and biotite. This rock occurs on an islet in a lake about 60° 01′ N. and 107° 41′ W. where it is permeated by microcline-rich pegmatite to form gneiss almost devoid of garnet and bearing many quartz-microcline augen about 1 cm. long.

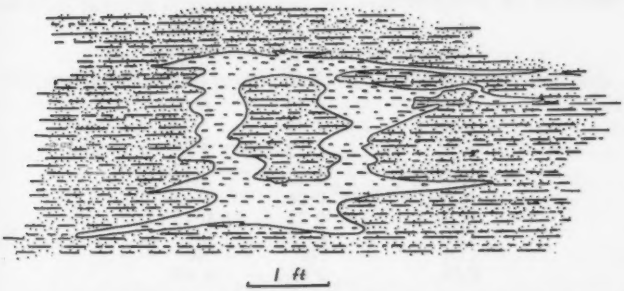
Some amphibolites, metasedimentary quartz-mica-gneisses, and pink microcline-rich syenites veining granodioritic gneisses are present. The first form nebulitic bodies and well-defined angular fragments in quartzo-feldspathic gneiss. Plastic deformation of the amphibolites often preceded their disruption by movements within the foliation plane of their host. In thin-section they consist chiefly of quartz, plagioclase, green hornblende, and biotite. The plagioclase (oligoclase-andesine) is fresh, twinned, and not zoned. Apatite, sphene, and iron

ore are accessory. Sometimes green diopsidic pyroxene is present although it is absent in adjacent migmatites derived from the amphibolite concerned. Scapolite replaces plagioclase in one amphibolite migmatized by granitic gneiss.

Gneisses with Granulite Fabric

(*a*) *Migmatites and Pseudomigmatites*

The European granulites are quartzo-feldspathic rocks characterized by a single megascopically conspicuous planar schistosity mainly due to parallel dimensional orientation of flat quartz lenses in a finer-grained quartzose matrix of equant crystals (Turner, 1948, p. 205).



Text-fig. 1.—Pink granitic gneiss veins of variable texture and appearance, but homogeneous composition, in granodioritic-dioritic gneiss. The assemblage displays a pronounced planar foliation due to alignment of dark minerals and highly lenticular quartz. Seen on a bluff on the S.E. side of a lake at lat. 60° 01′ N. long., 107° 35′ W.

Medium-grained gneisses with these and other petrofabric features characteristic of granulites are widely distributed in the Abitau Lake area and may be referred to below as "foliated gneisses". Granitic, granodioritic, and more basic varieties occur, each closely resembling the corresponding granoblastic gneisses in mineral composition but differing from them in fabric, megascopic appearance, and the following respects : garnet is rare in granodioritic-dioritic types ; epidote is often present in many varieties of gneiss as rods and grains associated with hornblende ; pyroxenes have not been noted.

Like their granoblastic equivalents, into which they are sometimes seen to pass, these gneisses are often migmatitic and their foliation is parallel to, or transects—always with little or no apparent displacement—the older migmatite structures. An example is illustrated in Text-fig. 1. Other instances include granodioritic gneisses with highly folded granitic veins crossed by the foliation but constant in thickness

throughout their lengths. In all cases quartz and feldspar are just as highly deformed in the granitic member of the migmatite as they are in adjacent granodioritic and dioritic members.

Besides migmatites the foliated gneisses form pseudomigmatites, as on Hostile Lake a few miles south-west of lat. 61° N. long. 106° W. On the south-east shores of this lake opposite a promontory on the large island in its centre there are large outcrops of dark grey medium grained quartzo-feldspathic gneisses with a pronounced foliation due to aligned dark minerals and elongated quartz. Pink feebly-foliated

TABLE I.

Chemical analyses of strongly-foliated grey gneisses forming pseudo-migmatites with pink granite.

	46	48
SiO_2 . .	67·48	67·04
Al_2O_3 . .	15·59	16·26
Fe_2O_3 . .	0·76	0·92
FeO . .	3·44	3·52
MnO . .	0·13	0·08
MgO . .	1·45	1·22
CaO . .	1·96	2·36
Na_2O . .	2·93	2·74
K_2O . .	4·20	4·18
H_2O+ .	0·96	1·12
H_2O- .	0·22	0·18
TiO_2 . .	0·59	0·57
CO_2 . .	Nil	Nil
P_2O_5 . .	0·03	0·03
	99·74	100·22

Analyst : W. H. HERDSMAN.

46. Medium-grained dark grey quartz-microcline-andesine-biotite gneiss with accessory apatite, sphene, zircon, and muscovite, showing strong planar foliation due to aligned biotite and elongate quartz crystals. South-east shore of Hostile Lake opposite a promontory halfway along the south-east shore of a large island in the centre of the lake.

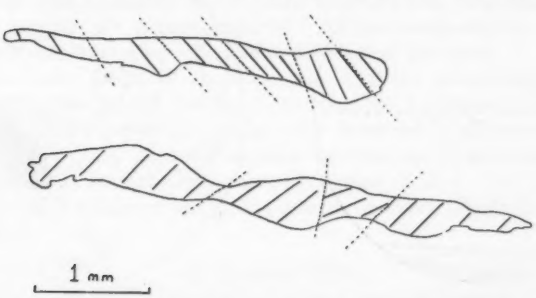
48. Medium-grained gneiss almost identical with spec. 46 in mineral composition and from the same locality as that specimen but paler in colour, very slightly garnetiferous and megascopically resembling *lit-par-lit* injection gneiss. Lenses and folia of highly elongate quartz and feldspar up to 1 cm. thick lie within the *ab* fabric plane in a finer-grained base of equant and lenticular quartz and feldspar.

granite occurs as layers within the foliation of the dark grey gneisses passing into the latter through grey rocks with relatively coarse quartz-feldspar folia and lenses megascopically resembling *lit-par-lit* injection gneiss and initially mistaken for such by the writer and his colleagues. Despite its field appearance this assemblage is not migmatitic but originated from one homogenous granite body by differential tectonization. Although the grey and dark grey gneisses are easily mistaken in hand-specimen for metasediments containing only moderate amounts of feldspar, under the microscope they are found

to be granitic in composition and modally very similar to the pink granite. Chemical analyses of them (Table I) are almost identical and granitic in character. The series dark grey gneiss—grey " lit-par-lit injection gneiss "—pink granite varies only in texture and the first two members owe their highly misleading megascopic aspect to tectonization. Similar pseudomigmatites elsewhere on Hostile Lake are sometimes associated with true migmatites. For example, on an islet southwest of the large island in the centre of the lake dark grey gneisses like 46 in Table I pass with little or no compositional change along the strike of their foliation into augen-gneiss and relatively granoblastic coarse gneiss of granitic aspect. Interbanded with this pseudomigmatitic assemblage are dark dioritic gneisses responsible for a true migmatitic layering dipping gently north-west parallel to the foliation.

(*b*) *Description of Fabric*

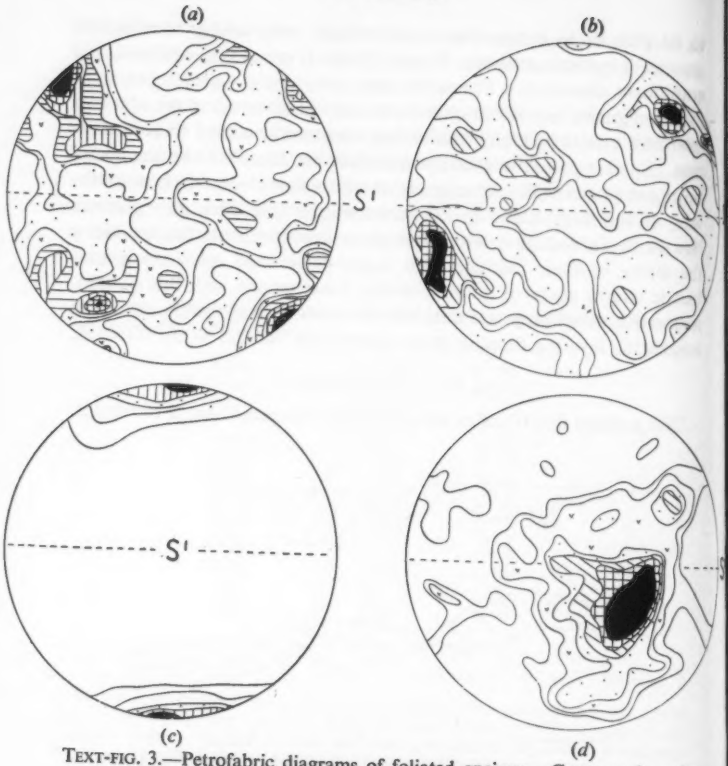
The gneisses described in the preceding sub-section are *S* tectonites.



TEXT-FIG. 2.—Typical examples of quartz lenses in the foliated gneisses drawn from pseudomigmatites on Hostile Lake. Dotted lines indicate rupture bands, solid lines quartz [0001] axes.

Generally without lineation they display a conspicuous planar foliation dipping steeply or gently north-west and striking parallel to the regional strike direction. This structure, which imparts a well-developed planar fissility so that the gneisses break readily into flaggy sheets under the hammer, is due to the parallel orientation of undeformed biotite plates up to 1 mm. long and numerous quartz and feldspar lenticles. Equant quartz and feldspar crystals are also present in the body of the rock and form some thin folia.

The highly elongate quartz crystals and super individuals (text-fig. 2) measure up to roughly 1 mm. in thickness and 0·5 cm. in length. Strain-extinction and rupture bands are invariably present and generally pronounced. Boehm lamellae are not seen. Most rupture bands tend



TEXT-FIG. 3.—Petrofabric diagrams of foliated gneisses. Contours in units per cent per one unit per cent area.

(*a*) Strongly foliated grey quartz-microcline-andesine-biotite gneiss forming pseudomigmatite on Hostile Lake at the same locality as spec. 46, Table I. Some conspicuous quartz-feldspar folia and lenses impart a " lit-par-lit injection gneiss " appearance to the specimen. 200 [0001] axes of lenticular quartz, contours 0·5–1–2–3–4–5.

(*b*) Chemically analysed dark grey foliated quartz-microcline-andesine-biotite gneiss forming pseudomigmatite (spec. 46, Table I) ; 200 quartz [0001] axes, contours 0·5–1–2–3–4.

(*c*) 150 poles to biotite cleavages in same slice as 3 (*b*), contours 1–5–10–15–20.

(*d*) Foliated pink granitic gneiss forming banded pseudomigmatite and migmatite on the west shore of a lake about 1 mile N.E. of Hostile Lake. Faint rodding of quartz occurs within the foliation ; 200 lenticular quartz [0001] axes, contours 0·5–1–2–3–4–5.

to parallelism with quartz [0001] axes and in some crystals these occur with rupture bands sub-normal to [0001]. Occasionally the former end abruptly against the latter as if truncated by them. It is possible by

normal petrographic methods to see that in most thin-sections [0001] axes of elongate quartz tend to be inclined in various directions to the foliation plane.

In the field a faint foliation inclined to *ab* is sometimes visible. Microscopically this is marked by slight granulation, trains of muscovite shreds, and deflection of biotite. Similar *S* planes, not megascopically visible, occur in many slices, often in pairs symmetrically inclined about *ab*. The sense of movement on these planes can seldom be determined. Microfractures of similar orientation or sub-normal to *ab* occur unaccompanied by granulation and often confined to individual lenticular quartz crystals.

Typical samples of foliated gneiss were petrofabrically analysed. The selective quartz diagram of pseudomigmatite text-fig. 3 (*a*) approaches orthorhombic symmetry. A non-selective diagram of the same slice made from 50 equant and 200 lenticular quartz crystals showed a similar pattern. The fabric also seems essentially homogeneous since a diagram of 200 quartz axes in a slice from the same hand-specimen cut at right angles to 3 (*a*) was comparable in many respects with 3 (*a*) when rotated into the plane of the latter.

The quartz fabric of the chemically analysed pseudomigmatite specimen 46 in Table I (text-fig. 3 (*b*)) resembles 3 (*a*) in its tendency for [0001] axes to avoid parallelism with directions in and normal to the foliation plane. Biotite in the same slice (text-fig. 3 (*c*)) is arranged in a partial girdle with single maximum normal to *ab*.

Text-fig. 3 (*d*) shows one strong quartz maximum slightly inclined to *ab*.

(*c*) *Origin of Fabric*

The granoblastic and the foliated gneisses were either simultaneously recrystallized side by side under different local tectonic conditions from a common parental migmatite, or the foliated gneisses are younger than, and have been derived from, the granoblastic gneisses. The second alternative seems most likely. A third possibility, that the granoblastic gneisses are younger than the foliated gneisses, can be discounted since no granoblastic gneisses have been seen with a close planar foliation in dark minerals that might have been inherited from rocks with granulite fabric.

Although the foliated gneisses closely resemble European granulites petrofabrically they differ from them considerably in their lower metamorphic state. They received their distinctive texture and structure during amphibolite facies metamorphism. Tectonization may perhaps have assisted the formation of epidote from hornblende to some extent since epidote, associated with hornblende in many foliated gneisses is absent from adjacent granoblastic gneisses. But other

factors must have been important in this connexion since some hornblendic foliated gneisses lack epidote.

Tectonization does not appear to have favoured the formation of either microperthite or myrmekite. Microperthite in granoblastic gneisses closely resembles that in foliated gneisses and myrmekite seems no more abundant in the foliated gneisses than in granoblastic types.

The movements responsible for the planar fabric of the foliated gneisses often appear to have largely involved squeezing normal to *ab* with little or no shearing parallel to that plane. It is difficult to see how extensive unidirectional laminar displacement can have taken place along the foliation of migmatites like those illustrated in text-fig. 1, or those containing folded granitic veins of constant width. Many foliated gneisses show subsidiary *S* planes symmetrically paired about *ab* that could be sets of conjugate shear planes developed during orthorhombic flattening movements normal to *ab*. The pseudomigmatite fabrics shown in text-fig. 3 (*a*) and (*b*) lack Sander's quartz maximum I, a deficiency that can be used to distinguish Saxon granulites deformed by " flattening " from those affected by extensive shear in *ab* (Sander, 1950, p. 177). Other features of these two diagrams also suggest that compression normal to *ab* has been important in their formation. It is suspected from normal microscopic examination that the quartz orientation of many foliated gneisses is similar to that shown in text-fig. 3 (*a*).

Extensive tectonic transport may, however, have affected one specimen with a single strong quartz maximum (text-fig. 3 (*d*)). The slight assymetry of total fabric in this specimen resembles that in certain Finnish granulites (Sahama, 1936) referred to complex strain or movement after the megascopic fabric had been impressed. A faint lineation, not seen in the other analysed specimens is visible on foliation planes and is due to slight rodding of quartz parallel to the trace of the foliation in text-fig. 3 (*d*).

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DEPT OF GEOLOGY,
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On the Origin of the Dogger Bank, in the North Sea

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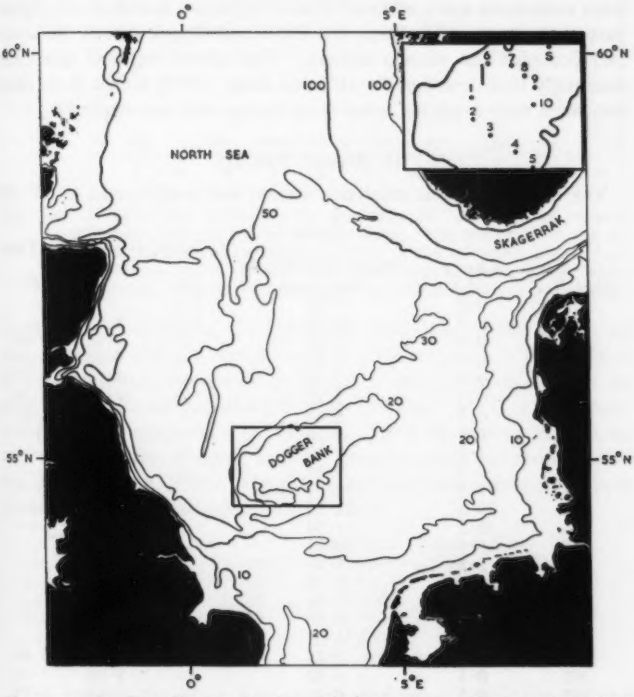
Abstract

A reversed seismic refraction station and some cores taken on the Dogger Bank, in the North Sea, are described. The absence of compacted sediments within the bank and the finding of only glacial or post-glacial sediments at its surface strongly suggest that the bank is a large moraine.

I. Introduction

In the North Sea there are a number of topographic features of uncertain origin. One of these, about which there has been considerable speculation, is the Dogger Bank. This isolated shoal lies on a line drawn from the northern tip of Denmark, along the south side of



Text-fig. 1.—The Dogger Bank, with inset figure showing the seismic station (line), coring stations (numbered), and littoral deposits of Stather (S). [Depths in fathoms.]

the Skagerrak, to Flamborough Head on the Yorkshire coast (Text-fig. 1). It stands more than 60 feet higher than the surrounding floor and is 160 miles long and up to 60 miles wide at the 20 fathom line. It is highest and widest and has an abrupt termination at the west end. Both the bank and floor to the south were inundated in early post-glacial times.

The origin of the bank has been variously attributed to rivers, tidal eddies, or to an extension of a scarp of Mesozoic rocks from the English coast; the importance of ice action has been shown by the occurrence of erratics from northern England and Scandinavia and of sands with heavy mineral suites from similar domains (Baak, 1936; Tesch, 1915). A recent review of this has been given by Charlesworth (1957).

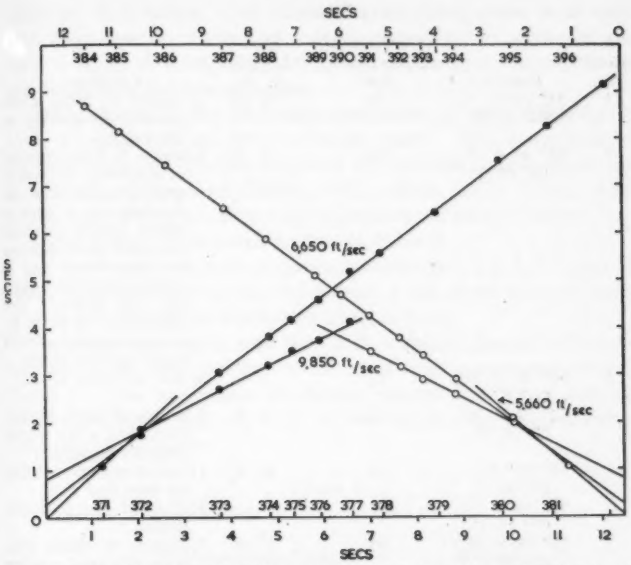
The latest information about its constitution has been obtained from some cores and a reversed seismic refraction station on the upper part of the bank. U.S. Ships *San Pablo* and *Rehoboth* took the cores and occupied the seismic station. The seismic method used was essentially that described by Hill and King (1953) except that, since two ships were available, sono-radio buoys were not required.

II. Seismic Results

The reversed seismic refraction station had a mid-point at 55° 10′

Table 1

Shot No.	*Charge (lb.).*	*Water Wave Travel Time (sec.).*	*Ground Wave Travel Time (sec.).* G_1	G_2	G_3
371	0·5	1·24	1·11	—	—
372	0·5	2·07	1·85	1·75	—
373	0·5	3·78	—	3·06	2·68
374	0·5	4·83	—	3·86	3·20
375	0·5	5·35	—	4·17	3·52
376	0·5	5·95	—	4·58	3·71
377	0·5	6·62	—	5·18	4·21
378	0·5	7·28	—	5·58	—
379	1·5	8·48	—	6·43	—
380	5·5	9·85	—	7·53	—
381	5·5	10·91	—	8·28	—
382	10·5	12·15	—	9·16	—
384	10·5	11·54	—	8·69	—
385	5·5	10·83	—	8·12	—
386	5·5	9·81	—	7·42	—
387	5·5	8·55	—	6·52	—
388	1·5	7·66	—	5·87	—
389	1·5	6·60	—	5·09	—
390	0·5	6·05	—	4·69	—
391	0·5	5·45	—	4·27	3·48
392	0·5	4·80	—	3·80	3·14
393	0·5	4·31	—	3·40	2·89
394	0·5	3·61	—	2·88	2·57
395	0·5	2·37	2·07	—	1·99
396	0·5	1·20	1·05	—	—



TEXT-FIG. 2.—The two time-distance diagrams for the reversed seismic refraction stations on the Dogger Bank. The numerals on the left of the figure represent the travel time of the refracted waves, those above and below that of the direct sound through the water (distance). The left-hand diagram is based on shots 371 to 382.

north, 02° 12′ east and the maximum separation of the ships used was 10 miles along a north–south line (Text-fig. 1). The weights of the twenty-five charges which were fired and the travel times of the seismic waves in the sea and sea floor are given in Table 1. These results are presented graphically in Text-fig. 2 and the stratal thicknesses and the velocities of compressional waves in them are shown below (M. and J. Ewing, 1951). The dip of the layers along the north–south profile appeared to be negligible in all cases.

Layer.	*Velocity (ft./sec.).*	*Thickness of layer (ft.).*	*Total depth below sea level (ft.).*
Water	4,920	120	120
3	5,660	1,250	1,370
2	6,650	1,850	3,220
1	9,850	> 8,300	> 11,520

The velocity for layer 3 is an assumed value which lies between that of sea water and the velocity for layer 2. It is thought that the thickness and velocity for layer 3 could have been found by making

TABLE 2

Core No.	*Position.*	*Uncorrected Sonic Depth, feet.*	*Core Length, ft. in.*	*Lithology.*
1	54° 58·2′ N., 02° 01′ E.	76	1 10	2 inches of fresh shells passing up quickly in fine sand.
2	54° 46·5′ N., 02° 02′ E.	96	12 6	Lower 3 ft. 9 in. consists of a mixture of stones, gravel, sand, and silt overlain by 4 feet in which coarse material becomes progressively less important and is interbedded with sand and silt layers. The uppermost 4 ft. 9 in. consists largely of thin sand and silt layers.
3	54° 39·5′ N., 02° 18′ E.	71	—	A few corroded shells.
4	54° 31·2′ N., 02° 39′ E.	58	3 6	3 inches of fresh, broken shells and a few stones beneath fine sand.
5	54° 23′ N., 02° 54′ E.	75	4 0	11 inches of shells grading up into fine sand.
6	55° 16·1′ N., 02° 15·5′ E.	108	—	Fine sand and corroded shells.
7	55° 14·8′ N., 02° 35·2′ E.	90	5 0	4 inches of shells with some fine sand grading up quickly into fine sand with some shell fragments.
8	55° 09·5′ N., 02° 47·0′ E.	39	5 0	11 inches of shells with a little fine sand, grading up quickly into fine sand with a few shell fragments.
9	55° 03·8′ N., 02° 55·0′ E.	82	8 0	3 feet with irregular layers of silty clay separated by fine sand and shells. Upper 5 feet consists of fine sand.
10	54° 55·0′ N., 02° 54·1′ E.	64	4 0	4 inches of fine sand with some shell fragments; above lies fine sand.

shots at distances of less than two miles. The estimated thickness of layer 1 is based on the assumptions that the basement has a velocity of 19,700 feet per second and that it was beyond the depth of detection of a shot about six miles long (M. and J. Ewing, 1951).

III. GEOLOGICAL EVIDENCE

The samples were taken with a Kullenberg-type piston corer with a main weight of 1,000 pounds and with a tube of internal

diameter of 2 inches. No smooth-walled lining tubes were used, and their absence, as well as the coarseness of the sediments and limited depth of water may each have been, in part, responsible for the shortness of the cores obtained.

The positions of the sampling stations are shown in Text-fig. 1; those in either line are about 10 miles apart. They cover a depth range of 6½ to 18 fathoms and were all taken on ground made predominantly of fine sand (Borley, 1923; Olsen, 1930; Jarke, 1956), which Baak (1936) has shown to be probably of glacial origin.

The lithology of the cores is given in Table 2.

Up to 5 feet of fine sand was proved at stations 1, 4, 5, 6, 7, 8, and 10, while older material was reached beneath 5 feet of the sand at station 9 and such material reached the surface at station 2.

The fauna associated with the sands consisted largely of lamellibranchs. The total number of valves of each species are given in Table 3. The importance of *Donax vittatus* and *Venus striatula* is underestimated because a lot of these shells were crushed during extrusion of two cores.

TABLE 3

Cores 1, 4, 5, 7, 8, and 10

Macroscopic Fauna.	*Total Number of Valves.*
Bitium reticulatum (da Costa)	5
Natica poliana Chiaje *alderi* Forbes	53
Cylichna cylindracea (Pennant)	1
Mangelia sp.	5
Clathrus sp.	4
Cardium sp.	2
Ostrea sp.	3
Corbula gibba (Olivi)	38
Donax vittatus (da Costa)	> 100
Gari fervensis (Gmelin)	17
Venus striatula (da Costa)	> 287
Ensis sp.	31
Spisula subtruncata (da Costa)	47
Mactra corallina Montagu	34
Lutraria lutraria (Linnaeus)	2
Phacoides borealis (Linnaeus)	7
Thyasira flexuosa (Montagu)	1
Dosinea exoleta (Linnaeus)	2
Lepton squamosum (Montagu)	1
Astarte compressa (Montagu)	15
Tellina fabula Gmelin	3
Dentalium entalis Linnaeus	3
Echinoid fragments	+

Most shells are rather worn although the sculpturing is visible on robust valves and there is still some of the original colouring on some of the relatively fragile shells such as *Mactra*. The fauna as a whole and the geographical distribution of the most abundant

species are in general agreement with the findings of Davis (1923). The lesser number of species found in the cores is probably the result of the relative smallness of the samples. A few uncommon species were not recorded by Davis but these do not alter the conclusion that the fauna is contemporary with the conditions existing on the bank to-day.

The shells and any small stones present were always restricted to the bottom of the cores, and none was present at the surface where they are known to occur to-day. There was an upward decrease in the size of shells and shell fragments in the basal beds, and in core 7 it was shown that this progressive change of grade was continued upward through the overlying sand. These features and the unusual orientation of the shells, with their concave interiors uppermost, require explanation. It is recorded by Rusnak (1954) that the original stratification of a sand core free of cementing material was liable to be seriously disturbed by the type of corer used on the Dogger Bank. It has been shown experimentally that a uniform mixture of the sand and shells of core 7 can be re-sorted within the core so as to resemble, most strikingly, the observed grading and shell orientation found in the cores. The conditions necessary to cause this were such as probably occurred within the tube as it was withdrawn from the sea floor. The shell beds are not, therefore, considered to be original structures.

Estuarine or tidal flat deposits with a present-day fauna were found at stations 2 and 9, about 35 miles apart (Text-fig. 1) and now beneath about 16 and 14½ fathoms of water, respectively. These sediments are thought to be of about the same age as the silty clay with a littoral marine fauna, taken from beneath 20 fathoms, which was described by Stather (1912). Some of the samples mentioned by him were in contact with early post-glacial peat, although the order of superposition was uncertain.

The littoral deposits of the two cores were, in the main, thinly bedded silts and fine sands, which were sometimes lenticular. In the lower 3 feet of core 9 such strata consisted of thinly laminated, grey, silty clay (in irregular layers up to 2 inches in thickness) separated by sand in which there were a few small bodies of mud. In core 2 the lower 3¾ feet consisted of a mixture of angular to rounded gravel and stones, scattered shells or fragments, and silty sand, which was grey when wet but mottled brown when dry. In the overlying 4 feet, coarse constituents progressively decreased in importance and beds of sand and silt became more apparent; some of the silt was thinly laminated. The overlying 4¾ feet consisted of thin, alternate layers of silt and sand; some layers were lenticular and certain sand layers were thinly bedded. This sequence was interrupted 13 inches

beneath the top of the core by a 2 inch bed of silty sand with pebbles and fragments of molluscan shells.

From $3\frac{3}{4}$ feet up to $8\frac{3}{4}$ feet above the bottom of the core the stratification was contorted. This could be an original structure; it is thought that it must be, in part, the result of differing friction of layers of coarse and fine sediments on the rough walls of the corer, as the core was taken. In the silts and sands of the upper part of the core the marginal distortion of bedding increased with increasing thickness of the layer of sand. Such an effect might be greater for even coarser materials.

The stones and gravel of this core were examined by Professor W. B. R. King, who concluded that they were derived from the north of England and Scotland, with subsidiary amounts from Norway, together with some flint (Table 4).

TABLE 4

Flints and a little Chalk.
Andesites, some porphyritic, of Cheviot Old Red Sandstone type.
Coarse red sandstone of Scottish Old Red Sandstone type.
Gneiss of (?) Norwegian type.
Lavas including Rhomb-porphyry of Oslo district.
Sandstones of unknown age.
Coal.
Partially compacted mud fragments.

The exotic rocks and the lack of size sorting of the lower third of the core are reminiscent of a glacial till, while the assemblage can be matched in the tills of Holderness. However, the marine fauna and the upward transition into stratified littoral marine deposits show that it was probably derived from such a deposit. The period of reworking must have been fairly brief for the coal and Chalk are too friable to have lasted long on a floor where hard pebbles were abundant.

The fauna of core 2 and the lower 3 feet of core 9 was entirely marine. There were twenty species of molluscs, the greatest variety occurring in the lower part of core 2 and the least in the mud layers of core 9. Only *Spisula subtruncata* was common and most of these valves were half grown (Table 5).

Foraminifera were a notable addition to the fauna of these cores, although virtually absent from the thin sand layers of core 9 (Table 6).

In the mud of core 9 the *Rotalia beccarii* were small and there were surfaces crowded with the calcareous tubes of *Spirorbis*. Some of these tubes were free while others were attached on one side to

the cuticle of some plant which occurred abundantly in fragments about 1 inch in length. Also attached to some pieces of cuticle was a marine alga, *Melobesia*, and an encrusting polyzoan.

The fauna in both cores is such as could be found around some margins of the North Sea to-day. It is Mr. Ovey's quite independent opinion that the foraminifera could have been taken from a littoral

TABLE 5

Macroscopic Fauna.	*Total number of valves.*	*Core 2 Lower 7 ft.*	*Core 9 Lower 3 ft.*
Spirorbis sp.	v.c.	—	v.c.
Calcareous worm tubes	+	+	—
Bitium reticulatum (da Costa)	3	3	—
Littorina littoralis (Linnaeus)	8	1	7
Natica poliana Chiaje *alderi* Forbes.	24	23	1
Gibbula cineraria (Linnaeus)	2	2	—
Mangelia turricula Montagu	3	3	—
Rissoa striata Montagu	10	—	10
Cardium edule Linnaeus.	1	1	—
Cardium exiguum Gmelin	1	—	1
Ostrea edulis Linnaeus	2	2	—
Corbula gibba (Olivi)	5	3	2
Donax vittatus (da Costa)	4	3	1
Gari fervensis (Gmelin)	1	1	—
Venus striatula (da Costa)	21	12	9
Venus ovata Pennant	1	1	—
Ensis ensis (Linnaeus)	7	4	3
Spisula subtruncata (da Costa)	60	—	60
Tellina fabula Gmelin	1	1	—
Abra alba (Wood)	1	—	1
Nucula turgida Leckenby and Marshall.	6	6	—
Pholas sp.	2	—	2
Echinoid fragments	+	+	+

— absent ; + present ; c. common ; v.c. very common.

or estuarine environment. A similar molluscan assemblage is found to-day near or in passages leading from the open sea into tidal flats of the Netherlands (Van Straaten, 1956). The stratified deposits from the deeper parts of these tidal flats (Van Straaten, 1954) are like those found in cores 2 and 9. Extensive reworking of earlier deposits occurs in such a situation and the observed gradation from ill-sorted coarse deposits up to stratified ones would not be out of keeping with the conditions.

The muddy deposits taken from 20 fathoms on the bank (Stather, 1912) contain a greater proportion of littoral species than was found in cores 2 and 9 and so were probably laid down in shoaler parts

TABLE 6

Foraminifera.	*Core 2. Coarse deposits 2¼ ft. above bottom of core.*	*Core 2. Bedded deposits 11½ ft. above bottom of core.*	*Core 9. Mud layers of lower 3 ft. of core.*
Nonion depressulus (Walker and Jacob).	−	+	−
Discorbis obtuse (d'Orbigny)	−	+	−
Discorbis sp.	−	−	+
Elphidium excavatum (Terquem)	−	+	−
Elphidium cf. *crispum*	−	+	−
Elphidium sp.	+	−	−
Rotalia beccarii (Linnaeus)	c.	−	+
Quinquiloculina sp.	+	−	c.
Planorbulina aff. *mediterranensis*	+	−	−
Cibicides lobatulus (Walker and Jacob).	+	−	−
Triloculina sp.	+	−	−

of such flats, some way from the main channels and the open sea. The fauna consisted of the following species:—

Flustra sp.
Littorina obtusata Linnaeus
L. rudis (Maton)
Rissoa membranacea (J. Adams)
Cingula semicostata (Montagu)
Hydrobia ventrosa (Montagu)
Anomia ephippium Linnaeus
Cardium edule Linnaeus
Montacuta sp.
Mytilus or *Modiola* sp.

The importance of this early work lay in the association of peat with the littoral deposits, although the sequence is not known with certainty. Peat, on or near the bank, has been dated as early post-glacial in age, pollen zones IV or V, and so the littoral deposits were probably laid down by the rising waters of the post-glacial North Sea.

IV. The Origin of the Dogger Bank

The velocity of compressional waves in the uppermost layer of the seismic station was put at about 5,660 feet per second. This lies within the range of values for the superficial deposits which occur around the North Sea from Scotland to Denmark and elsewhere (Drysdale, 1956; Brown and Robertshaw, 1953; McFarlane, 1955; Willmore, 1949; Heiland, 1946; Brockamp, 1934). This layer is about 1,250 feet thick, which is not unreasonable since an even greater thickness, of marine Pleistocene alone, has been found under Holland (Lagaaij, 1952). The Dogger Bank, with a height of only 60 feet, must be made of superficial sediments but cannot be the seaward prolongation of a ridge of Mesozoic rocks, as has been suggested.

The Pleistocene age of the bank is shown by the mammalian bones

and by the heavy mineral suites and erratics derived from northern England and Scandinavia. Clay with stones (Stather, 1912) may represent actual till and the pebbly deposit of core 2 must have been derived from such material lying close at hand. It seems that Belt (1874) was correct in identifying the bank as a huge moraine.

The precise age of the bank is intimately related to the age of the Holderness drifts. These must be of about the same age since there is little difference in the amount of weathering of their surfaces (King, 1955). In the field, Penny shows them to be younger than the buried cliff seen clearly at Sewerby and traceable down the east side of the Wolds. King considers it likely that the mammalian bones on that beach are Eemian and so the drifts were all laid down during the last glaciation. The same view is held by Valentin (1953) who found the topography of the Holderness drifts to be as fresh as the Wurm-Weichsel drifts of north-west Germany. It would be strange if the Dogger Bank could be older than this for the earlier ice spread far to the south of the Dogger Bank. Valentin (1955) considers the abrupt west and northern faces of the bank to mark the limits of the English–Scottish and Scandinavian ice sheets of the last glaciation, respectively.

The surface of the bank has probably not changed much since it was inundated by the post-glacial North Sea, for peat has been found at numerous points on its top and sides (dated samples are all early post-glacial in age). Tidal-flat or near-shore marine deposits with a contemporary fauna are also still in place. In core 9 these are overlain by clean-washed sands, proved to 5 feet in some cores, which must lie as a mantle over much of the bank and probably represent the glacial deposits reworked by the present sea.

V. Discussion

Chalk, flints, and other Mesozoic rocks have been found in the drifts of eastern Scotland and it has been concluded that such rocks must have been exposed on the floor of the northern part of the North Sea. The finding of Chalk and flints in the pebbly drift-like material of core 2 may mean that Chalk also outcropped further south, nearer to the Dogger Bank.

The probable age of layers 1 and 2 can be deduced only from the similarity of their velocity characteristics and thicknesses with rocks on land. The nearest exposures are of Chalk at Flamborough Head, 90 miles distant. There, the velocity of compressional waves increases with the age of the rock, ranging from 9,900 to 16,400 feet per second (Laughton and Stride, 1957). Although the determination was made in the laboratory, and so does not take account of the bedding planes and joints, it is likely that these have a small effect because of the depth to which these rocks are probably buried beneath the bank.

Similar values were found in north-west Germany by intensive field determinations tied to bore-holes (Bentz and Closs, 1955). If the Chalk beneath the bank is similar to that occurring to east or west rather than at Cambridge or the English Channel, which have a lower velocity (Bullard, *et al.*, 1940; Hill and King, 1953), then layer 1 consists of Chalk. On thickness and velocity considerations it might also contain some rocks from upper Carboniferous to Jurassic in age.

If the above interpretation is correct, then it is likely that layer 2 consists of Tertiary sediments. These are found in the arc of countries facing the south side of the Dogger Bank and have been found east of the Orkney Isles, at the northern end of the North Sea (Newton, 1917). The probable 2,000 feet of such sediments beneath the bank is less than occurs under Holland (Pannekoek, 1956). The velocity of compressional waves for such sediments, at the depth of burial where they probably occur beneath the bank, would be about 7,000 feet per second (Faust, 1951), which is fairly close to the observed value for layer 2.

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NR. GODALMING.

The Geology of the Snøfjella and Dovrefjella in Vestspitsbergen

By John Preston

(PLATE I)

Abstract

The area yields marbles, schists, and quartzites, probably of Hecla Hoek age, a series similar in lithology to those in the Kongsfjorden region. Their structure and metamorphic condition fit in with the general picture of Caledonian trend and of increasing orogenic activity westwards. Later faulting along the western edge of a graben has broken this ground up into independent blocks as witnessed by the disposition of the Devonian conglomerates. The youngest rocks are a southerly outlier of the plateau basalts best seen around Woodfjorden, remnants of at least two flows are preserved, both of olivine basalt rich in olivine phenocrysts and carrying inclusions of a more alkaline rock type.

I. Introduction

The geological exploration of this area to the north of Ekmanfjorden was planned by the Queen's University Spitsbergen Expedition 1957 and field work, confined to the Snøfjella and Dovrefjella, was undertaken during three weeks in the summer of that year. I am indebted to the leadership of Mr. P. Robson and Dr. W. Schwarzacher, to its members and to those who supported it, especially the Everest Foundation.

Various members of both Isachsen's and Ahlmann's expeditions had made earlier visits to the area and Isachsen's topographic map (1916) was used as a guide for the daily excursions, but the geological information, shown on Orvin's map of Spitsbergen (1940), was limited to the observations of Hoel and Holtedahl (Holtedahl, 1926), who reconnoitered the mountain ranges and noted the occurrence of alternating zones of crystalline limestone and mica schist.

The geological map (Text-fig. 1) is based on the results of F. B. Kennedy's topographic survey and shows the major rock divisions only. The oldest rocks exposed probably belong to the Hecla Hoek Formation, a series of calcite and dolomite marbles, mica schists, quartzites, and conglomerates. These strike more or less parallel to the mountain ranges but a complex structure coupled with poor exposure make their subdivision difficult. Erosion has moulded them into well rounded forms now flanked by precipitous cliffs where continued glacial activity has bitten into their sides.

Basal conglomerates of the Old Red Sandstones overlie this crystalline basement and by their disposition help to define the fault block system. Steeply dipping conglomerates build the west side of the Snøfjella and their high crags make a prominent landmark for traveller and geologist alike. The existence of similar strata on the

Dovrefjella is inferred from loose material seen in scree and fault breccia and from exposures on the most southerly knoll of this range.

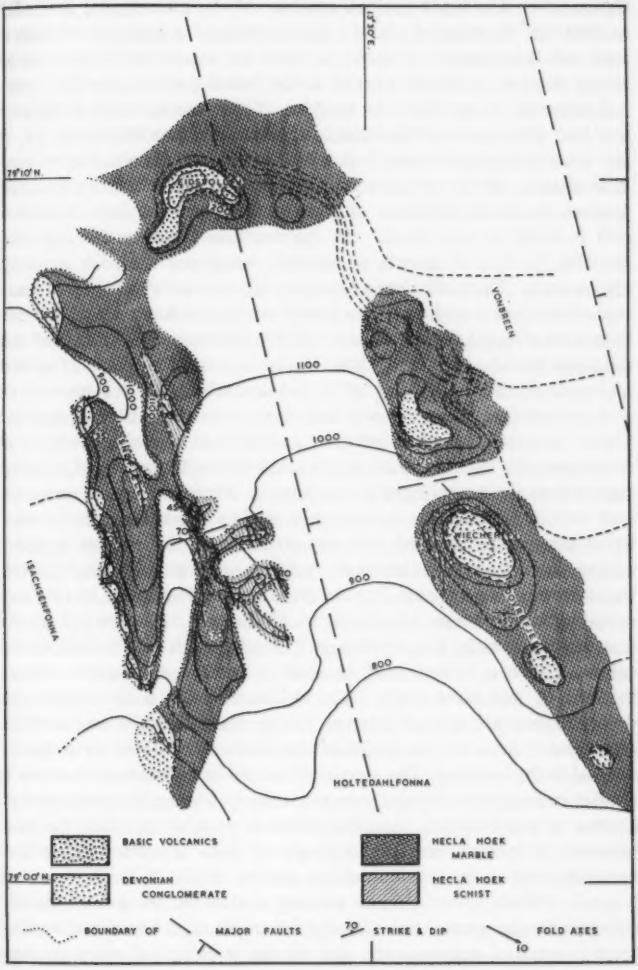
Basic volcanics, probably of Tertiary age, cap the isolated Eidsvollfjellet in the north, and like the Devonian conglomerates and Hecla Hoek schists show up in marked contrast to the pale coloured marbles by reason of their dark colour in outcrop and scree. These lavas occur closely related to a probable fracture which runs parallel and close to the Vonbreen fault, a dislocation whose association with volcanic activity has long been established.

The highland ice of this area fills the broad valleys excavated along the major fault lines and moves into the ice of the Tre Kroner glacier. This movement on the Isachsenfonna is evidenced by trails of boulders from Devonian crags and also by the hanging of the small corrie and valley glaciers over its margin. The mountain ranges themselves are under a thick cover of snow and ice, cornices 15–30 m. thick top the exposed cliffs, and most summits are snow domes.

II. Metamorphic Rocks

There is a metamorphosed succession of limestones, dolomites, cherts, clays, silts, sandstones, and conglomerates. Excepting the rudites no original clastic textures can be recognized with certainty though many structures of a sedimentary character may still be observed. Recrystallization has proceeded within the greenschist facies, a response to a penetrative deformation which in most outcrops has been constrained to the bedding of the rock. Grain size has increased in consequence but most specimens collected are still, partly or wholly, too fine-grained for a regional petrofabric study. The finest grained marbles occur in the Dovrefjella, an average grain size of 3–8 μ in dia. comparing well with a non-metamorphic limestone, e.g. a calcite mudstone. Many of these show an incipient recrystallization to the coarser textures which prevail in the western range, the only indication within the area of an increasing metamorphism in this direction.

Calcite marbles.—These are by far the most abundant rock type, especially in the Dovrefjella. They may be blue, grey, cream, or buff coloured and massive or flaggy in structure. Fine grained quartzose layers and lenses are often associated and the absence of sericite mica in many of these is taken to indicate original chert whilst its presence would point to a silty or sandy intercalation. Thick chert beds, 1–2 ft. in thickness, are occasionally seen especially along the south-eastern wall of the valley glacier which almost breaches the Snøfjella. Even the pure marbles contain a number of small, isolated, and apparently well rounded quartz grains, the boundaries of which show corrosion by the calcite. Their average diameter lies between 30–50 μ.



TEXT-FIG. 1.—Geological map of Snøfjella and Dovrefjella.

Often a banding, seen best in thin section, of alternating finer and coarser grained layers occurs parallel to the original bedding. This variation may reflect the amount of plastic deformation experienced,

though even the finest grained marbles of the Dovrefjella, in so far as they can be sampled, show a good preferred orientation of both *c* axes and twin planes. *C* axes and poles to twin planes usually made strong maxima or girdles normal to the bedding and major fold axes.

Laminated calcite-dolomite marbles. These too are well developed and best seen in the cliff sections of the Snøfjella (see Plate I, fig. 3); a few occurrences in the easterly range differ in having laminae up to $\frac{1}{2}$ in. in thickness. Their colour is typically blue-grey and the fine laminae average $\frac{1}{10}$ in. in thickness with pure calcite grading into dolomite-rich material in each band. On the weathered surface the dolomite rhombs, 80–90 μ in length, are etched out giving the rock a sandy appearance. Rhythmic deposition may account for this rapid alternation of limestone and dolomite limestone or a dolomitic replacement may have affected the upper layer of thin limestone beds; indeed the dolomite rhombs with their clear rims to a clouded core full of calcite inclusion would be typical of a dolomitized rock, yet movement and recrystallization make top and bottom features unrecognizable. These marbles may have an even greater extent in the Snøfjella if calcite marbles with dolomitic knots and schliers, Plate I, fig. 4, may be regarded as their metamorphic equivalent. From a range of outcrops and collected specimens an almost complete transition can be seen from almost undisturbed fine laminated rock to coarser grained calcite marbles with thin lenses and schliers much enriched in dolomite to those with augen some $\frac{1}{4}$ in. in dia. of pure dolomite. In this last example the dolomite occurs not as idiomorphic rhombs but as an interlocking mosaic, the crystals still clouded with tiny inclusions of calcite. Such a texture may be seen as occasional patches in thin sections of laminated rock. The orientations of both calcite and dolomite crystals are of interest for in the relatively undisturbed types the *c* axes to the dolomite rhombs are confined to a girdle normal to the bedding. The associated calcite in the same rock shows a similar orientation with a strong tendency to maximum development normal to the bedding. Another point of contrast between the two minerals is seen in the development of twin lamellae: these are common even in the smaller calcites yet the largest dolomite remains a single crystal. At the other extreme *c* axes for the calcite matrix still possess the same kind of preferred orientation but the dolomite mosaic gives a scatter over the whole area of a stereographic projection. Such behaviour may be accounted for in the greater strength of dolomite relative to calcite.

Dolomite marbles.—Rocks free from calcite are far less common and more restricted in their occurrence. Examples in the Dovrefjella are rare and in the Snøfjella they appear restricted to one horizon west of the mica schists. Calcite marbles and cherts are intercalated

Unusual sedimentary structures characterize these rocks; mineral-lined cavities might suggest a secondary replacement or coupled with irregular markings and textures an original reef formation, see Plate I, fig. 2. Other beds show a regular banding, Plate I, fig. 1, with graded beds some ½–1 in. in thickness with the darker blue top to a bed brecciated at regular intervals through the succession.

All these marbles are intersected by calcite veins following the prominent joint directions. Most fracture surfaces are coated with a thin veneer of tufa or calcite crystals, a deposit which obliterates any sign of movement on the joint.

Mica schists.—Schistose marbles and calcareous schists are common along the boundaries of this group but within it mica schists and flaggy schists are typical. The latter have thin quartz-rich layers separated by mica-rich folia. Chlorite may occur along with sericite and graphite, and chlorite-quartz veins are common segregations in the more highly folded rock. The principal schistosity is still parallel to bedding and only in the more contorted schist does a false cleavage develop. All the Snøfjella schists are black in colour and in the ridges which run off the eastern margin of the range give jagged and even pinnacled outcrops. In the Dovrefjella thin brown schists are associated with the marbles.

Quartzites and conglomerates.—These occur as intercalations in the Snøfjella mica schists and up to three beds have been recorded in one section, though the possibility of repetition by folding could not be ruled out. The quartzites are glassy and never quite free from sericite, the mica may produce a flaggy parting and carbonate minerals are sometimes concentrated in thin marble seams. Quartzose pebbles up to ½ in. in size are drawn out into elongate lenses, and in the northern part of the schist group an intraformational conglomerate occurs with similar pebbles greatly elongated in a calcite matrix. Thin quartzites have also been seen in the western slopes of Wiechertfj.

Structures.—Deformation has thrown the above rocks into a a series of N.–S. trending folds whose axial planes are now steeply inclined towards the west. In the Snøfjella these folds plunge mostly to the N.N.W. at 10–20 degrees, an inclination which is reversed in the Dovrefjella where steeper plunges occur to the S.S.W.

Poor exposures make it very difficult to determine the succession and the overall general structure, and the following interpretation is offered based on the known distribution of rock types and the relatively small scale structures seen in cliff sections. This applies to the western fault block where a fair cross section of the range can be examined in the south-eastern wall of the valley glacier and along the flanks of the schist ridges. The northerly plunge of fold axes in the schists coupled with an apparent nosing of the outcrop in this direction

suggests an anticlinal structure with the schists overlain by blue-grey laminated marbles. The recurrence of these marbles and their metamorphic equivalents along the western edge of the Snøfjella might be due to their repetition in the limb of a corresponding syncline with the dolomites occupying a structurally higher position in the succession. Only occasional glimpses may be had of large folds of 30–45 m. amplitude and then an overturning towards the east is seen, a feature inferred from the stereographic projection of all strike and dip measurements.

Details of these folds show that the rocks have behaved in both brittle and plastic fashion. Carbonate rocks are well known for the ease with which they flow under conditions of regional metamorphism yet throughout their thickness and extent they show a competent behaviour resulting in concentric folds. Too sharp a flexure has produced fracture and brecciation and small folds can be traced near their core into slides and crush rock, as illustrated in Plate I, fig. 5. Closely spaced tension cracking in the well bedded marbles is a common feature; many are now healed by a network of calcite veins as are those in the marble of Plate I, fig. 3, and others by continued movement have been broken into an irregular breccia similarly cemented. A plastic deformation is more restricted in occurrence and found only where the marbles are associated with schists. Here flow folds of ptygmatic appearance are traversed by well foliated shear planes. The best development, see Plate I, fig. 6, occurs on the north and north-west slopes of Wiechertfj, where, to judge from the scree, a coarse textured graphitic schist also occurs.

Jointing is closely spaced in all the rocks, and scree fragments are 3–4 in. in size as a result. So shattered is the rock by frost action that many apparent screes still show the dominant joint directions of the parent rock. Joints perpendicular to the fold axis are prominent, complementary sets of joints oblique to these are common, and a plot of all fractures measured in the field or from the orientated hand specimens shows them to be normal to the bedding and often in two sets diagonal to the tension joints.

Brecciated zones trending E.–W. are very common within the marbles, and large volumes of rock have been broken up in this way, but although the trend of the zone is apparent little information can be gleaned on movement direction. The greatest zone defines a fault which breaches both mountain ranges and produces spectacular topographic features. In the Dovrefjella a deep narrow pass allows the plateau ice to escape down on to Vonbreen, whilst in the Snøfjella due west of this a deep cleft through the high marble cliffs marks the site of what is probably the same fault. Many of these faults to judge from the colour of their breccias are post-Devonian in age.

The structure of these rocks cannot be fully appreciated until they are corrected for the dip of the overlying Devonian. In both mountain ranges the marbles and schists have parallel strike and the folds a similar inclination of their axial planes, steep to the west. After correction these structures in the Snøfjella become relatively flat-lying and it becomes difficult to reconcile them as products of the same period of compression which affected the Dovrefjella. One way of accounting for this anomaly is to postulate movement on the major faults in pre-Devonian times.

Correlation.—On the foregoing evidence correlation can only be tentative. Throughout the Snøfjella one might suggest a sequence of dolomite and calcite marbles, laminated marbles, and mica schists with quartzites and conglomerates, and suggest too that they occur in this order with increasing age. Not even the Dovrefjella rocks can be placed in this succession and further afield greater difficulties arise. Northwards by some 25–35 miles and on the same side of the Raudfjord–Vonbreen fault Hoel (1914) records schists, quartzites, and limestones of Hecla Hoek age. Holtedahl (1914) makes another reference to these formations and gives their strike as N.N.W.–S.S.E., a trend in fair agreement with that of the mountain ranges described above. To the west around Kongsfjord, Orvin (1934) has mapped similar rock types and Tyrrell (1924) on Prins Karls Forland describes a Ferrier Peak Series predominantly of carbonate rock and in a similar metamorphic condition. West of the Devonian Graben the Hecla Hoek is represented by a great formation of marbles associated with a group of mica schists and quartzites. For occurrences east of this graben one can turn to the summaries and correlations worked out by Harland and Wilson (1956) and gain the general impression that thick developments of carbonate rocks occur repeatedly in their Upper and Middle Hecla Hoek divisions. One can also agree with their placing of the Western Spitsbergen marbles tentatively in the upper Middle Hecla Hoek. It is only possible to make comparisons in greater detail with Orvin's work around Kongsfjord. Either side of Blomstrandbreen occurs a series of mica schists with quartzites overlain structurally by a thick development of marbles. Because this sequence persists over a wide area Orvin accepts it as the original order of deposition. The schists he equates to the Quartzite and Mica Schist Series on Bröggerhalvøya with the reservation that in this locality the succession may be inverted as indeed are the younger formations when caught up in the movements of Tertiary age. Thus it may be possible that the Snøfjella mica schists with intercalated white and yellow quartzites are equivalent in age to the Quartzite and Mica Schist Series of Kongsfjord whilst the overlying marbles correspond to those of Blomstrandbreen and Marble Island.

III. Devonian

Holtedahl (1926) described a limestone conglomerate taken from the west side of the Snøfjella which reminded him strongly of rocks seen in Raudfjord in 1909. Such polymict basal conglomerates occur, almost to the exclusion of any other rock type, in the corries and buttresses along this western flank. The pebbles and boulders are almost all of marble types, occasionally a quartzite is represented whilst the fissile schists appear as small fragments in the matrix. The pebbles are all well rounded and poorly graded; beds of smaller pebble size do occur and even thin seams of arkose are intercalated.

Sometimes an imbricate structure can be recognized with the longer axis of the pebbles orientated parallel or perpendicular to it. All these examples gave current directions which on the west flank of the Snøfjella trend approximately east–west and show a derivation of material from the east, contrary to the spread of the deltas of Red Bay conglomerates for the area to the north, Orvin (1940).

The characteristic colour is chocolate-brown, due to strong iron staining in the matrix; greenish tints may discolour the rock along joint planes and in the finer-grained arkose along the bedding. Bedding is very well developed and all strata are waterlain. The thickness must be of the order of 5–600 m. at least.

The relationship of these conglomerates to the underlying Hecla Hoek is of interest for the unconformity offers some unusual features and topographic forms. This plane of unconformity approximates to the present day erosion surface, for many of the hill slopes lie close to it, and bears evidence of pot holes and solution hollows filled with red conglomerates and arkoses. The differential weathering of these rocks leads to peculiar landforms.

Structure.—The disposition of the Devonian must differ for the two mountain ranges. In the Snøfjella it flanks the western slopes building a long escarpment breached only by small corrie and valley glaciers. The strike is slightly north of north-west and the dip 50 degrees to the west and remarkably constant; at only one locality were the strata disturbed and steeper dips associated with thrusting. No exposures of these rocks were visited in the Dovrefjella but the scree heads yielded numerous fragments of red conglomerate and sandstone. The latter is rich in calcite and may be seen *in situ* as a joint infilling, the angular quartz and calcite rhombs of the matrix being associated with a pore infilling of a fibrous mineral, probably anhydrite. Some of the conglomerates must be fault breccias for they contain fragments of this red calcerous sandstone and indeed most fault planes and infillings show a rich brown discoloration. The most southerly knoll of the range, passed on the homeward journey, showed

typical Devonian outcrops with a gentle dip to the south. On this evidence it is believed that if Devonian strata no longer cap the hill summits they have not long been removed by denudation.

This discrepancy in dip for the Devonian of the two mountain ranges consigns them to different fault blocks in the absence of any evidence of folding. Three faults must then traverse the area from N.N.W. to S.S.E., two of which have long been recognized:—

(1) A fault along the length of the Isachsenfonna separating Hecla Hoek schists and intrusive granites from H.H. marbles and overlying Devonian. The dip of the latter must indicate a considerable downthrow to the east and it is probably a continuation of the Red Bay Fault of Holtedahl (1914) with a probable pre-Wood Bay Series age.

(2) A fault along Vonbreen, a continuation of that from Raudfjord, with again a considerable downthrow to the east of the order of some 1,200 m.

(3) A fault between the Snø- and Dovrefjella downthrowing to the east. The southerly extension of this line meets an apparently unbroken escarpment of Devonian rocks and again a pre-Wood Bay Series age must be inferred.

Tilting of the Snøfjella block exaggerates the throw and a better picture of the fault system may be had by considering the total throw across the whole zone. West of the Isachsenfonna the Hecla Hoek schists build mountains up to 1,100 m., whilst east of Vonbreen Devonian strata occur down to a level of 180 m. These are classed by Føyn and Heintz (1943) in the Kapp Kjeldsen division of the Wood Bay Series and it seems likely that basal conglomerates of the Red Bay Series would occur below, for such rocks are recorded by Hoel and Holtedahl (1911) from the lower reaches of Vonbreen in probable faulted contact with the lower Devonian grits. This gives a minimum displacement of 900 m. down to the east. Only one minor fault with a similar trend and throw has been encountered in the marbles of the eastern Snøfjella.

Correlation.—No fossils have been collected which would help date these beds and the Holtedahlfonna obscures their relationships to the fish-bearing strata of the Tre Kroner country. Holtedahl's comparison (1926) would be more acceptable if the term Red Bay facies were used, for such an horizon of basal conglomerates might well be diachronous. The maps of the English, Norwegian, Swedish Expedition (1939) figure them as Red Bay Series and since all the surrounding country can be assigned on faunal evidence to the Kapp Kjeldsen Division this is a reasonable correlation.

IV. Basic Volcanic Rocks

This occurrence of igneous rocks lies much further south than the outcrops described by Hoel and Holtedahl (1911) for the Woodfjord

region. The dark outcrops and scree, easily mistaken at a distance for Devonian, cap the isolated hill of Eidsvoll and lie close to or above a major fault. Material occurs *in situ* on the south-west shoulder close to the cairn; elsewhere a coarse scree indicates its extent along the south facing slopes of the hill. Thick snow cover obscures the remainder and the map boundaries are therefore tentative. Allowing for this snow cover a minimum thickness of 100 m. must occur—a figure not inconsistent with the thicknesses recorded for the north and north-east outliers. The rock is without doubt an extrusive lava and portions of at least two flows are exposed to view; the vesicular and slaggy top of one is overlain by the massive base and centre of a succeeding flow. Even the red stained ropy and corded lava surface is beautifully preserved. The rock varies in grain size from very fine to glassy and contains a number of coarser-grained inclusions usually of well rounded aspect, somewhat vesicular, and ranging in size from a fraction of an inch to several inches in diameter.

Petrography of Lava.—The lava is a porphyritic olivine basalt, with phenocrysts of olivine and a few plagioclases set in a matrix of olivine, augite, and plagioclase; the last two minerals show a tendency to an ophitic relationship.

Olivine occurs as phenocrysts in both rounded and idiomorphic grains ½–1 mm. long, or as agglomerations of such grains. A small amount of corrosion tends to produce a rounded outline but most grain margins are sharply zoned with a more idiomorphic fayalite-rich rim. This zoning is present from the core but the greatest change in optical properties occurs in the rim. Commonly a red brown alteration stains the inner edge of this rim with a clear outgrowth beyond it. Small granules in the ground mass of the lava may be similarly stained thus dating the alteration. Sometimes the whole outer shell is discoloured in this way. Some agglomerations show the rim developed only on the free boundaries of the grains, a feature indicating coalescence before crystallization of the groundmass. This rim too is the only olivine indented by the plagioclase.

The composition of the olivine has been determined by measurements of 2*H* on the Leitz 5-axis universal stage adopting the refinements suggested by Hallimond (1950). Discrepancies between measurements around *X* and *Z* were never eliminated and amounted to 2–3 degrees, an error reported by other workers. The average fayalite content of the phenocryst cores worked out at 26 per cent with a range from 7–45 per cent; this is beyond the errors inherent in the method and suggests a variation in composition between the olivine individuals. Change in composition at the rim ranges from 20–30 per cent making the fayalite content of the later growth 46–56 per cent. Groundmass olivines were more difficult to measure but an average figure of 50 per cent fayalite

content, with little variation from one grain to the next agrees well with that of the phenocryst rim.

Pyroxene occurs in small crystal plates that are colourless to very pale grey or even faintly lilac-tinted in thin section. It is a clinopyroxene with a positive $2V = 57$ degrees and a Z to C extinction angle of 40 degrees. It is probably of augitic composition.

Plagioclase both as occasional phenocrysts and groundmass laths defines a vague flow structure through the rock. The larger laths are of medium labradorite with compositional zoning over a narrow

TABLE 1

	1	2	3	4
SiO_2	50·19	49·75	50·29	52·94
TiO_2	1·47	1·38	1·20	4·31
Al_2O_3	14·39	14·14	15·91	13·33
Cr_2O_3	0·027	0·015	n.d.	n.d.
Fe_2O_3	2·04	3·45	2·12	4·93
FeO	9·60	8·80	7·91	6·83
MnO	0·18	0·16	0·16	0·29
NiO	0·11	0·02	n.d.	n.d.
MgO	8·99	8·92	7·53	2·99
CaO	7·93	7·69	8·61	6·73
Na_2O	3·20	3·15	3·85	5·10
K_2O	0·87	0·97	0·95	1·52
P_2O_5	0·63	0·62	1·10	n.d.
$H_2O -$	0·08	0·25	0·31	0·25
$H_2O +$	0·12	0·44	0·31	0·55
	99·827	99·755	100·25	99·77

1. Porphyritic lava, Kapp Auguste Viktoria, Woodfj. Analyst, Prof. M. Dittrich.
2. Vesicular lava, Kapp Auguste Viktoria, Woodfj. Analyst, Prof. M. Dittrich.
3. Porphyritic lava, Eidsvollfj. Analyst, J. Preston.
4. Inclusion in lava, Eidsvollfj. Analyst, J. Preston.

range throughout, this may even be oscillatory. Inclusions of pyroxene in the cores possess an irregular blebbed shape that suggests an original liquid inclusion. The groundmass feldspar is of similar composition and it too forms the residuum of the rock.

Magnetite, hematite scales, and apatite needles are common accessories and any vesicles in the rock may contain a little calcite.

The vesicular top shows a large proportion of dark glass in a highly oxidized condition full of magnetite grains and hematite scales. The phenocrysts described above are all present but swallow-tailed plagioclase laths are the only groundmass representative. It may be that the olivine phenocrysts are not primary crystallates but derived from other sources. A comparison with other Woodfjorden lavas seems desirable since more than one age group is present there. A chemical analysis, see Table 1, shows close agreement with the

Kapp Auguste Viktoria lavas and a marked contrast to the trachydolerites of the Quaternary–Recent volcanic cones of the same volcanic province. The average modal analysis of 7–8 per cent olivine phenocrysts, 8 per cent olivine granules, 20–25 per cent pyroxene, 1–2 per cent plagioclase phenocrysts, 55–60 per cent groundmass plagioclase, and 2–3 per cent iron ore also helps in this comparison with the Cretaceous–Tertiary basalts of the Woodfjord region.

Petrography of Inclusions.—Inclusions of hypidiomorphic granular to sub-ophitic rocks show a marked contrast in grain size, mineralogy, and chemical composition to the host lava.

Olivine is typically absent or present in small quantities. It assumes an unusual prismatic habit and has a high fayalite content of 75 per cent.

Lilac-brown titanaugite with a faint pleochroism is characteristic and occasionally fringed by greenish aegerine-augite or aegerine. At its margin it forms a vermicular intergrowth with the plagioclase. The positive $2V = 55$ degrees and the Z to C extinction angle 49 degrees. Aegerine also appears in small granules as one of the last minerals to separate.

Plagioclase feldspar shows progressive zoning from acid andesine to acid oligoclase; in some grains the core is homogeneous and distinct from the zoned shell around it. Orthoclase feldspar is now represented in the interstices of the rock.

Iron ore is particularly abundant, a few hematite scales occur but the bulk is magnetite of lamellar inclining to skeletal habit. Apatite needles are common whilst calcite may again appear in the vesicles.

The chemical analysis is given in Table 1 and the mode averages at 0–4 per cent olivine, 27–31 per cent pyroxene, 12–13 per cent iron ore, 50 per cent plagioclase, and 6 per cent orthoclase. Some comment might be made on the origin of these inclusions in the light of this analysis. The mineralogy and texture points to a cognate inclusion rather than an accidental xenolith; the higher silica content, a distinct increase in total alkalies, an increase in K_2O over Na_2O and also in the Fe: Mg ratio all suggest a late differentiate of a basic magma. Marbles underlie these plateau lavas to a considerable depth and over a large area and it seems probable that some reaction would occur in the feeding conduits between the magma and the carbonate country rock producing a marginal facies of alkaline type. In other localities around Woodfjord, inclusions described in detail by Backlund (1911) prove to be of ultrabasic rock types and possibly equivalent to the olivine phenocrysts rather than the inclusions of the Eidsvoll lava.

A final point in this comparison with the Cretaceous-Tertiary basalts of Woodfjord is the position of the flows at 1,200 m. on what is probably a peneplaned surface. Such a platform of Cretaceous to Tertiary age

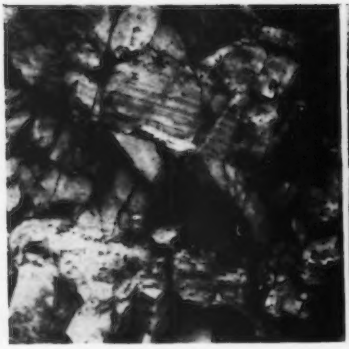


FIG. 1.

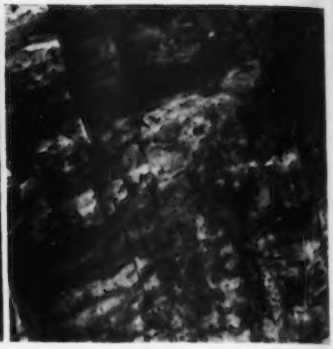


FIG. 2.

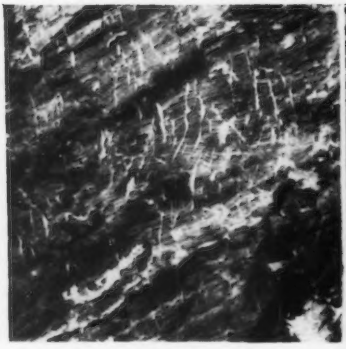


FIG. 3.

FIG. 4.

FIG. 5.

FIG. 6.

METAMORPHIC ROCKS AT SNØFJELLA AND WIECHERTFJELLET.

can be recognized to the north and north-east, a factor in the dating of the basalts, and at the present day tilted to the north. Hoel (1914) gives an elevation for it of 500 m. in the north and 1,100 m. in the south, an inclination which if continued a few miles further south would reach an elevation of approximately 1,200 m. on Eidsvollfjellet.

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EXPLANATION OF PLATE I

Fig. 1.—Dolomite marble from the western flanks of the Snøfjella. The rock is well laminated with a gradation in colour from grey to blue-grey in each lamina; these are brecciated at regular intervals throughout the succession. The laminae are approx. $\frac{1}{4}$ in. thick.

Fig. 2.—Dolomite marble from the western flank of the Snøfjella showing irregular reef type structures. The average joint spacing is $1\frac{1}{2}$ in.

Fig. 3.—Laminated marble from the western flanks of the Snøfjella traversed by numerous calcite filled tension cracks. Small offsets along these joints are visible. The laminae are $\frac{1}{10}$ in. thick.

Fig. 4.—Calcite marble with dolomitic knots and schliers from the western flanks of the Snøfjella. The photograph shows an etched surface three times natural size.

Fig. 5.—Folded calcite marble from the Snøfjella with flaggy bedding some 5–6 in. thick. Brittle fracture is seen in the sharply folded beds and the small fold has slid against the adjacent strata.

Fig. 6.—Flow folding in calcite marble from Wiechertfj.

The Pre-Cambrian Rocks of Southern Co. Wicklow (Ireland)

By W. E. Tremlett

Abstract

A sedimentary formation beneath the Bray Series is found to have an extensive outcrop in southern Co. Wicklow. Evidence is given of the Pre-Cambrian age of both series. They are exposed in a Caledonian anticlinorium, which has been cut by thrusts and high-angle faults, but they had suffered strong orogenic deformation and prolonged erosion before the unconformable deposition of Lower Palaeozoic strata.

I. Introduction

THE Bray Series has long been recognized as one of the main stratigraphical units of south-eastern Ireland, outcropping in two large anticlinal areas (one extending S.W. from Bray, Co. Wicklow, and the other to the S. and S.W. of Cahore Point, Co. Wexford), separated by a synclinorium containing Ordovician and possibly Silurian strata (e.g. Jukes and Haughton, 1859). It has generally been shown on the maps of Geological Survey as of Cambrian age, but there has hitherto been uncertainty regarding the south-western limit of outcrop of the " Cambrian " rocks of the northern area. This resulted from the use of different criteria for the recognition of the rocks assigned to this system.

In the early mapping of this area Wyley appears to have taken as the distinctive feature of the " Cambrian ", the presence of quartzites, absent from the overlying " Ordovician " slates (which included the author's Clara Series). He consequently grouped the author's Knockrath Series with the Bray Series as the " Cambrian " of S.E. Ireland and recognized these rocks as extending S.W. to the Ow River, with large areas of outcrop around Ballinacor Mountain and Coolgarrow (Kinahan, 1878, pp. 13 and 15). Jukes, however, took the thick grits and purple slates (of the Bray Series) as characteristic of the " Cambrian " and consequently terminated the outcrop of this system some nine miles further N.E. than Wyley. To the S.W. of this boundary he failed to distinguish the quartzite-bearing Knockrath strata from the Clara Series and succeeding rocks, all of which he mapped as Ordovician. This version of the geology was used by the maps of Geological Survey until 1901, when a compromise was effected by Egan and McHenry (under the directorship of A. Geikie) taking Jukes' boundary as the limit of the main outcrop of the " Cambrian " but to the S.W. using the more prominent quartzite outcrops (of the Knockrath Series) as the basis of " Cambrian " inliers.

In order to resolve the uncertainty regarding geological boundaries and to discover the structural details of this area, the south-western end of the Bray anticlinorium has been remapped. A lower, quartzite-bearing, semi-pelitic series has been separated from the Bray Series on account of its marked difference in lithology, and is named the Knockrath Series. This leaves the boundary of the Bray Series substantially the same as the " Cambrian " boundary mapped by Jukes, but to the S.W. of this the outcrop of the Knockrath Series is found to be far more extensive than the " Cambrian " inliers of Egan and McHenry and more similar to the distribution advocated by Wyley.

II. Stratigraphy

The main stratigraphical formations of this area are:—

4. Dunganstown Sandstones
3. Clara Series
2. Bray Series
1. Knockrath Series

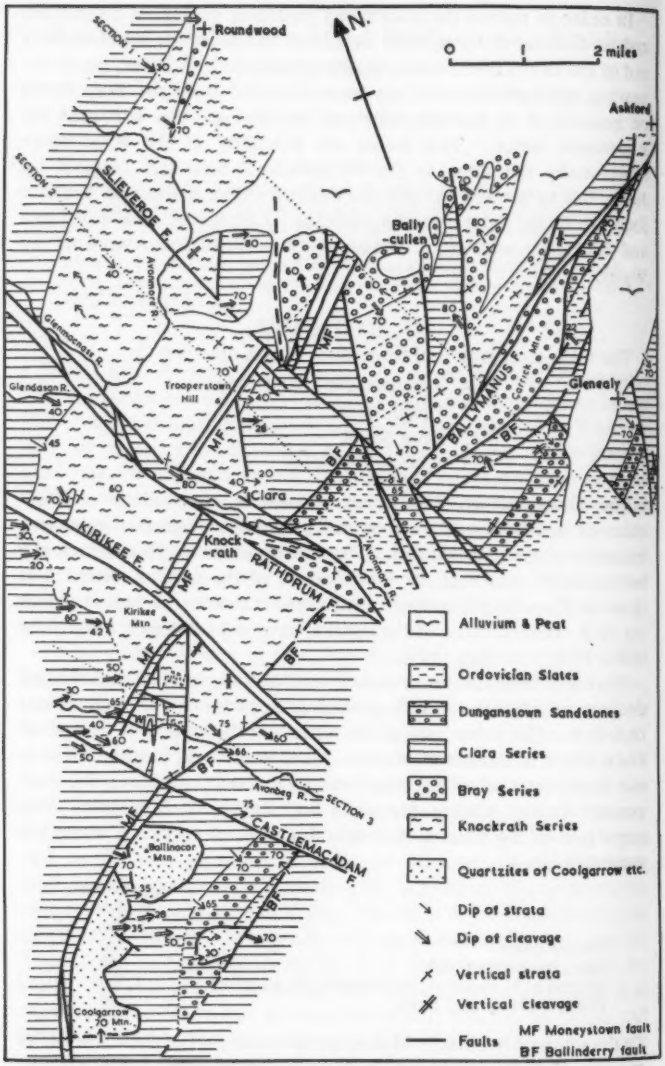
The Dunganstown Sandstones consist of alternations of buff-coloured sandstone and siltstone with grey and buff slates, with a total thickness of about 1,500 feet. They have yielded no fossils from the north-western flanks of the synclinorium of the Arklow district, but in the south-eastern limb similar sediments at a similar distance beneath the thick volcanic series of the district, have yielded Arenig graptolites (Elles, 1910, Tremlett, 1959).

The Clara Series is almost entirely argillaceous, and has an estimated thickness of 8,500 feet. Black, or dark grey, slates are the predominant rock-type. The lower part of the series is well-exposed N. and E. of Clara where it consists of massive, black mudstones passing upwards into black slates. Similar rocks, strongly cleaved throughout, are well-exposed around Kirikee Mountain and Ballinacor Mountain. The upper part of the series is well seen S. and E. of Glenealy, where the succession is:—

	Approximate thickness in feet.
Mauve slates	180
Hard, blue-grey slates	350
Striped light and dark-grey slates (silty in parts)	1,500
Hard, medium-grey slates	350

To the south of Ballinacor Mountain the upper part of the Clara Series consists of light-grey slates, lacking the prominent colour-banding seen near Glenealy.

This series, lying beneath the Dunganstown Sandstones of probable



TEXT-FIG. 1.—Geological map of the area S.W. of Roundwood and Ashford (Co. Wicklow). (Igneous intrusions omitted.)

Arenig age, and containing some brachiopods, would appear to belong to the Cambrian System. Small, poorly preserved brachiopods from about 1·3 miles E.S.E. of Trooperstown Hill have been examined by Dr. Stubblefield, who describes them as resembling *Acrotreta* or *Micromitra*, but no fossils allowing more accurate identification or more precise dating have yet been found in this series.

There are not sufficient distinctive horizons in the upper part of the Clara Series to allow definite determination of its relationship to the Dunganstown Sandstones, but in the Glenealy district the persistence for over a mile of mauve slates immediately beneath the sandstones suggests a conformable relationship. It should be noted, however, that along the south-eastern flanks of the synclinorium of the Arklow district, about 25 miles to the south, the sandstones appear to have been deposited directly on the Bray Series (Tremlett, 1959), having completely overlapped or overstepped the Clara Series, while still further south they lie unconformably on the Rosslare Migmatite Series (Baker, 1955, p. 65).

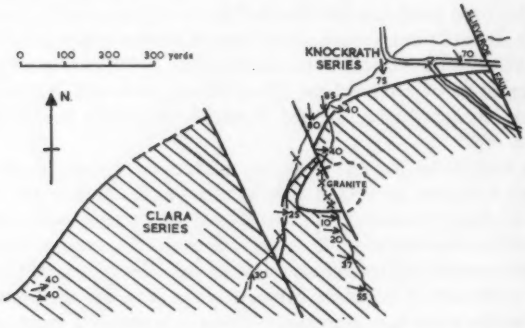
The Bray Series consists of purple mudstones or slates at the base, overlain by green, grey (and occasionally purple) greywackes, which occur in thick, massive bands interbedded with purple (or sometimes grey) slates or mudstones. In a few places the arenaceous beds have suffered dynamic metamorphism to quartzite. It is estimated that only about 1,000 feet of strata are exposed in the area, but the upper part of the series is not here preserved. There is probably a much greater thickness to the N.E., closer to Bray, and in other parts of south-eastern Ireland.

The Knockrath Series consists generally of rapid alternations of dark-grey or black slates and light-grey quartzitic siltstones, not more than a few inches in thickness. The strata are normally intensely contorted and shattered and the arenaceous bands more or less recrystallized. The rocks of the series commonly contain crystals of pyrite. The thickness of the group cannot be measured directly on account of its intense folding, but it is estimated that over 4,000 feet of strata are exposed, and the base of the series is nowhere seen. About 600 feet from the top of this series a bed of massive, grey and green grit, more than 50 feet thick, exposed about 1·8 miles W. of Carrick Mountain and 2 miles S.W. of Roundwood, resembles Bray sediments, but is succeeded by a thinly-bedded alternation of black slates and thin siltstones, such as makes up the major part of the Knockrath Series. This similarity of sequence in widely separated districts and the interbedding of Bray and Knockrath types of sediment suggest a conformable relationship between the two series.

The unconformity at the base of the Clara Series can be seen from its general relationship to the underlying rocks, resting sometimes on

Bray strata and sometimes on the Knockrath Series. In more detail, an unconformable contact with Knockrath strata is well-exposed on the eastern slopes of Trooperstown Hill (Text-fig. 2), where massive, grey mudstones dip to the E.S.E. at about 30°, and rest on near-vertical slates and quartzitic siltstones of the Knockrath Series, with bedding and cleavage striking generally a little N. of E.

The unconformity between the Clara Series and Bray Series is best illustrated at Ballycullen, where the strike of greywackes of the Bray Series, only a little N. of E., makes a large angle with the margin of a syncline of Clara Series trending 30° E. of N.



TEXT-FIG. 2.—Geological sketch-map of Trooperstown area, showing the unconformity between the Clara and Knockrath Series.

In addition to these particular examples from the contact of the Clara Series and older strata, there is a general difference of strike of bedding and cleavage throughout the area, between the E.N.E. direction of the Knockrath and Bray Series and the N.N.E. to N.E. alignment in the Clara Series and later sediments. This difference of strike was recognized by Jukes and Wyley (1856, p. 33) as evidence of an unconformity, between the " Cambrian " (Bray Series) and surrounding sediments, but in their example of an unconformable relationship at the junction of the townlands of Moneystown and Kilmullen (1856, p. 34) the outcrops appear to be separated by a fault of the Moneystown fault-belt.

The author's conclusion that the Bray and Knockrath Series are Pre-Cambrian is based on their stratigraphical position beneath the Clara Series, of probable Cambrian age, from which they are separated by a marked unconformity, and on the structural evidence of an early, strong orogenic deformation of these rocks, about which more details will be given in the following section. It should, however, be noted here that a Pre-Cambrian age for the Bray Series has previously been

advocated on account of lithological similarity to parts of the Mona Complex of Anglesey (Blake, 1888, pp. 534–6; Greenly, 1937). The supposed Cambrian age of these strata was based on the presence of *Oldhamia* and other problematical fossils (Sollas, 1895, Cole, 1901, Ryan and Hallissy, 1912), but no definite Cambrian fossils have ever been reported.

III. Structure

(*a*) *The Pre-Cambrian Orogeny*

The evidence given above, of unconformity at the base of the Clara Series, reveals an important deformation of the Knockrath and Bray strata prior to the deposition of the Lower Palaeozoic sediments. On the eastern flanks of Trooperstown Hill the Knockrath Series are near-vertical, the argillaceous sediments altered to slates and the arenaceous bands to quartzites, while the overlying basal mudstones of the Clara Series dip away from these rocks at a gentle angle and have here escaped cleavage during the ensuing Caledonian orogenesis.

The general strike of individual beds and of the boundaries between the Bray and Knockrath Series indicates that this orogenesis produced a series of folds trending about E.N.E., but in the less competent Knockrath strata the strike is sometimes variable. The cleavage of the slates of both series usually shows the same E.N.E. orientation and high-angle inclination.

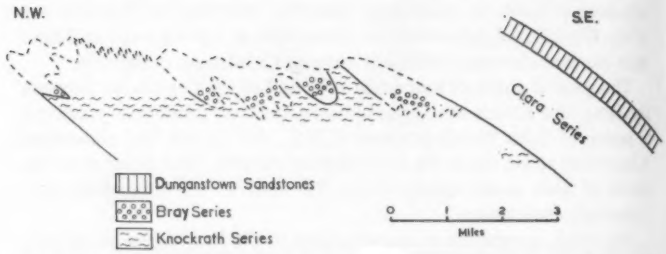
The thick, competent arenaceous beds of the Bray Series show consistent steep dips, indicative of a system of large isoclinal folds. The less competent beds of the Knockrath Series, however, generally show extreme contortion, in which acute, minor, isoclinal folding can be recognized, with lenses of more or less recrystallized siltstones squeezed out from the attenuated limbs into the cores of the folds. The cleavage of the argillaceous rocks shows an axial-plane relationship to these minor folds. On account of the similarity of strike of the Bray and Knockrath strata and the apparent conformity of the two series, noted in the previous section, the greater intensity of deformation of the Knockrath strata than that generally shown by the Bray Series is attributed entirely to the difference in degree of competence of the rocks.

It should be noted that the deformation shown by the Knockrath strata, the general dynamic metamorphism of the contained siltstone bands, and the occasional alteration of arenaceous beds of the Bray Series to thick quartzites in parts of the folds where the rocks suffered maximum stress, far exceed any folding or dynamic metamorphism of similar Lower Palaeozoic sediments achieved by the Caledonian orogenesis in this district or the adjacent Arklow district (Tremlett, 1959).

No evidence of faulting during the Pre-Cambrian orogenesis has been discovered, but it would be difficult to detect on account of the general lack of distinctive beds in these rocks and the subsequent complex Caledonian history.

The exposure of Bray Series in the north-north-eastern parts of the Caledonian anticlinorium and Knockrath rocks in the south-south-western portions may be due in part to a regional dip of the strongly folded Pre-Cambrian rocks towards the N.N.W., but must be attributed partly to a pitch of the folds towards the E.N.E. The pitch may have been imposed during the orogenesis or may reflect a subsequent regional tilt before erosion of the Pre-Cambrian rocks and deposition of the Clara Series.

It may be noted that the general strike and cleavage directions produced by the Pre-Cambrian orogenesis in southern Co. Wicklow



TEXT-FIG. 3.—Diagrammatic section of the anticlinorium in the vicinity of the Slieveroe fault, with faults omitted.

are similar to those found in the Mona Complex of Anglesey and those of the Rosslare Migmatite Series of the south-eastern corner of Ireland (Baker, 1955).

(*b*) *Caledonian Folding*

The main effect of the Caledonian orogenesis was the production of a large overturned anticlinorium, the subsequent erosion of which has exposed the Pre-Cambrian formations at the surface. The general trend of this fold is about 30° E. of N. The dip of the basal Clara mudstones at Trooperstown Hill (Text-fig. 2) indicates the inclination of the south-eastern limb at about 30°, while at the north-western contact of Pre-Cambrian rocks and Clara Series the inclinations of the cleavage indicates a general dip of the contact to the S.E. at about 40°. A diagrammatic representation of the form of the anticlinorium in the vicinity of the Slieveroe fault is shown in Text-fig. 3. The presence of numerous outliers of Clara Series between pairs of N.N.E. rift-faults, a little to the N.E. of the Slieveroe fault, suggests the upper surface

of the Pre-Cambrian rocks was not far above the present general erosion level.

When traced S.W. from the Slieveroe fault the anticlinorium appears at first to narrow rapidly and pitch a little, but there is little further change in its form between the Rathdrum and Castlemacadam faults.

Caledonian folding of Knockrath strata near their contact with the Clara Series is well-exposed S. of Kirikee Mountain, on the slopes of the Avonbeg valley, where the Knockrath Series and the basal portion of the Clara Series show a series of isoclinal folds dipping E.S.E. at 70°, with an axial-plane cleavage well-developed in the black slates of the Clara Series. At more than 100 yards from the margins of their outcrop the Knockrath rocks often show an essential E.N.E. strike, though with cleavage parallel to the Caledonian isoclines and with some minor corrugations having axial-planes parallel to this direction. Closer to the contact with the Clara Series, the arenaceous bands within the Knockrath Series develop prominent zig-zag folds with long, approximately N.N.E. limbs, and axes that are more or less vertical. As the contact is approached these folds show increasing length and parallelism of their limbs, while an increasing tendency to division of the siltstone bands into separated fragments of isoclinally folded rock indicates strong shearing parallel to the contacts.

(*c*) *Caledonian Faulting*

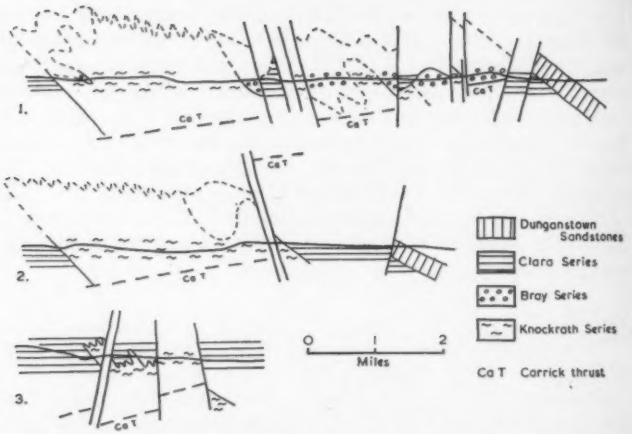
The main fault structures are found to be in accordance with those of the Arklow district (Tremlett, 1959), and, as in that area, faults have a considerable influence on the surface distribution of the rocks. They belong to four different sets, which are, in order of formation, low-angle thrusts to the S.E. and high-angle N.E., N.W., and N.N.E. faults.

Some prominent quartzites are found where thrusts have caused widespread dynamic metamorphism of the Pre-Cambrian rocks of the overlying nappes. They are best seen at Carrick Mountain where a nappe of prominent, massive white quartzites has been carried over Dunganstown Sandstones and the succeeding slates. Occasional lenticles of purple slates among the quartzites indicate that they have been formed by dynamic metamorphism of Bray Strata. Prominent jointing in the quartzites above the thrust and cleavage in the slates immediately beneath it show the Carrick thrust to dip north-eastwards at about 20°.

The lower, Coolgarrow thrust in the S.W. of the area separates klippen of prominent quartzites forming all the highest land, from the Clara Series and Dunganstown Sandstones exposed on the lower ground. Comparison of these quartzites with the less severely metamorphosed Pre-Cambrian rocks shows some similarity to the Bray Series, in their large proportion of arenaceous rock, but closer likeness

to the Knockrath Series in the general thinly-bedded nature of the succession, the absence of purple slates and the occasional presence of grey or black slates. They are unlike any of the Lower Palaeozoic strata of this region, and are interpreted as part of the Pre-Cambrian succession, but their exact stratigraphical position is not known.

The main strike-faults are the Ballinderry and Moneystown faults, which appear originally to have had respectively a south-easterly throw of about 5,000–7,000 feet and a north-westerly throw of about 1,000 feet. There has, however, been further movement on several occasions



TEXT-FIG. 4.—Approximately N.W.–S.E. sections to illustrate the structure of the area. Actual lines of section shown on Text-fig. 1.

along parts of these faults, which consequently now have larger displacements in places. During formation of the north-westerly faults the Moneystown fault absorbed most of their dip-slip movement, and though they are generally of oblique-slip, sinistral type in the eastern parts of the area, they are essentially strike-slip faults to the N.W. of this strike-fault.[1] There may have been movement along parts of the Ballinderry fault at the same time. During later phases of faulting in the area to the east, a large upthrow of the Castlemacadam fault persisted as far west at the Moneystown fault, but a large elevation of the block between the Slieveroe and Castlemacadam faults was mostly absorbed along the Ballinderry fault.

[1] The Slieveroe fault effects a slight dextral displacement of the strike-faults, but the position is complicated by its termination against the overturned edge of the anticlinorium. A few miles to the S.E. and for most of its course this fault shows a sinistral tear of 0·8 miles.

As a result of these various phases of movement the present effects of the north-westerly faults between the two strike-faults are as follows (Text-fig. 4). The Slieveroe fault, with a south-westerly upthrow estimated at 7,500 feet, brings to the surface a level much beneath the Carrick thrust (and is also responsible for the final disappearance to the S.W. of the Bray Series, apart from a lenticle in the Rathdrum fault-belt). A south-westerly throw of about 7,000 feet along the Rathdrum fault-zone again brings down a level above the Carrick thrust, but a very large upthrow S.W. of the Castlemacadam fault brings the lower, Coolgarrow thrust up to the surface.

The N.N.E. faults, which in places control outliers of the Clara Series, do not appear to have a large throw. Their apparent termination against the N.E. and N.W. faults suggests that they formed late in the structural history of this area. They often occur in pairs of rift-faults.

IV. Conclusions

A lower stratigraphic unit, the Knockrath Series, lies with apparent conformity beneath the Bray Series, and has an extensive outcrop in southern Co. Wicklow. A strong Pre-Cambrian orogenesis caused a series of steep-limbed E.N.E. folds in both these series, with intense minor folding in the Knockrath strata, and dynamic metamorphism of some of the sediments of both series. Prolonged erosion exposed the Knockrath strata extensively in the S.W. of the area before the Clara Series, of probable Cambrian age, was deposited unconformably on the Bray and Knockrath rocks.

In Caledonian times an anticline, sharply overturned towards the N.W., was formed in this area, and the rocks were subsequently displaced by powerful thrusts towards the S.E. and high-angle N.E. and N.W. faults. Smaller N.N.E. faults in the north-eastern part of the area have in places let down outliers of Clara Series into the general area of Pre-Cambrian rocks.

Acknowledgments

I wish to express my gratitude to Professor T. N. George for reading and criticizing the text of this paper, and to Dr. C. J. S. Stubblefield for examining the fossils. A grant towards research expenses from Glasgow University is gratefully acknowledged.

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The Intrusion-Breccia of Dunmore, Co. Donegal

By W. J. French and W. S. Pitcher

(PLATE II)

Abstract

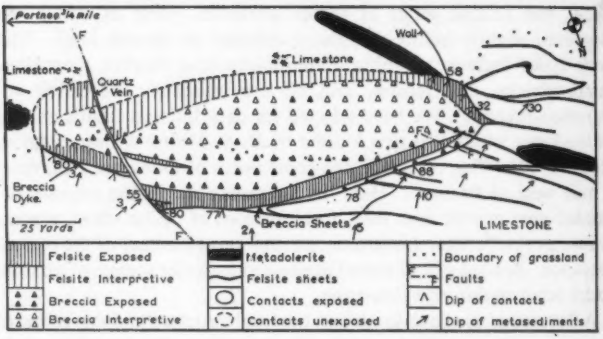
A small plug-like body is made up of an intrusive breccia contained within a ring of felsite. The felsitic matrix of the breccia is of composite origin and certain textures may indicate contemporaneous breaking of crystals. Attention is drawn to the association of this diatreme with the suite of felsite, hornblende lamprophyre, and hornblendite intrusions clustered around the diapiric pluton of Ardara.

CLUSTERED around the diapiric pluton of Ardara is a varied but related series of minor intrusives, most of which were emplaced slightly before the pluton reached its present level. Their rock types include appinitic amphibolites and diorites, hornblende lamprophyres, and felsites, and all are intimately associated with intrusion-breccias. We have selected for description a felsitic example of the latter which was first located by R. S. Mithal during a regional study (1952). This occurs on the coast north of Dunmore Hill, nearly a mile west of Portnoo. Here the Dalradian succession consists of a bedded grey marble with thick intercalations of pelitic schist, together known as the Portnoo Limestone, an important member of the regional sequence. Beaded sills of metadolerite and irregular masses of appinitic rocks occur within this limestone.

A flat recumbent fold dominates the local structure and this is sharply cross-cut and completely undisturbed by a small, steeply-bounded elliptical intrusion. The outcrop of this intrusion (Text-fig. 1) measures some 170 by 45 yards and is divisible into three parts: a discontinuous marginal breccia up to three feet in thickness surrounds a more continuous dyke-like ring of felsite up to 18 feet across, and this itself encloses the core of breccia which makes up the greatest part of the mass. Numerous thin felsitic sheets have been intruded along the bedding-planes of the country rock and are closely connected in time and place with the main intrusion; some of these sheets are transected by the intrusion, one cuts it, and yet others form apophyses of it. Further, the sheets are especially abundant near the intrusion.

The main felsite at both its inner and outer contacts mingles with the blocks of the breccia, a relationship seen to perfection on the foreshore, where the zonal boundaries dip steeply parallel with the outer contact of the body. The evidence available at the ends of the main outcrop (see Text-fig. 1) gives us the clear impression of an oval plug-like mass. Downward divergence of the first few feet of the extreme south-western contacts may be evidence of proximity to the roof of the intrusion.

The felsite of the ring is a rather variable rock with respect to both composition and grain-size. The margins are finer-grained than the central parts and in thin section often show a marked flow structure. Some discontinuous internal contacts sharply limit coarse patches, and vesicle-like cavities are not uncommon. Thin sections reveal phenocrysts of brown hornblende and plagioclase set in a groundmass of quartz, interstitial to or intergrown with laths of a second type of sodic plagioclase. Tiny flakes of biotite are abundant. Pyrites and primary calcite are important minor constituents along with apatite, sphene, and clino-zoisite. The term " felsite " is used here in a very general sense and a clear connection with the lamprophyres is provided



TEXT-FIG. 1.—Geological map of the Dunmore Intrusion-Breccia. High-water-mark lies near the bottom of the figure. The stone wall provides a location point.

by those rocks which have a higher proportion of the mafic minerals. In passing we may note that the peripheral sheets have much the same composition but generally lack the larger altered feldspars described below.

In the finer-grained rocks the hornblende is well-formed and largely unaltered. In the coarser types it is ragged in outline and partially or wholly pseudomorphed by mats of biotite with sphene, or by fine aggregates of a light, greenish-brown amphibole, with or without biotite. Both these new mineral aggregates may be dispersed and scattered into the body of the rock. The zoned phenocrysts of plagioclase have irregular margins which sometimes cut across the zones; the latter may centre on a point outside the present margins of the grain.

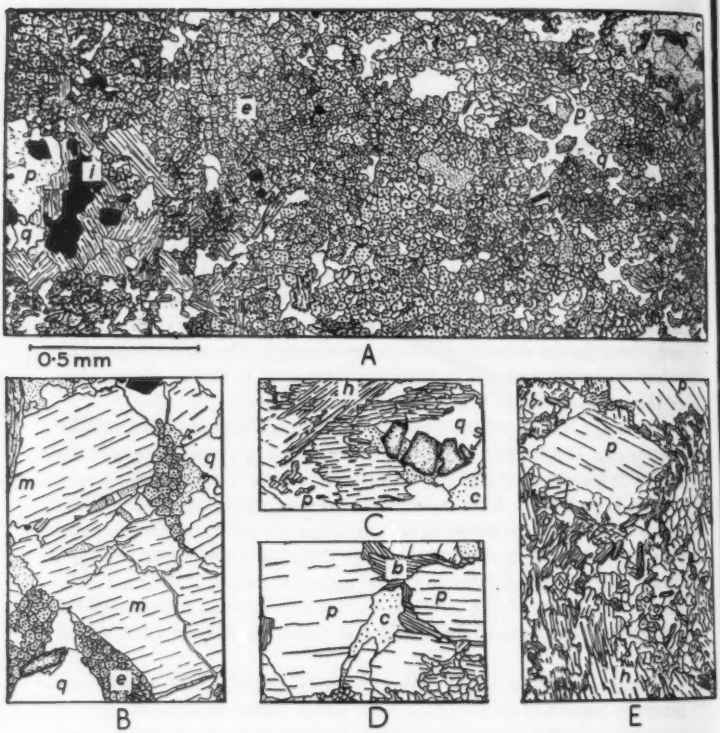
Robust flakes of white mica occur within, and may wholly replace, these larger plagioclases. The textural relationships between phenocrysts and groundmass, and between the groundmass minerals them-

selves, are very variable and complicated; there are intergrowths, inclusions, and irregular margins; certain types of embayments suggest resorbtion. Reaction is clearly demonstrated and corrosion strongly suspected.

The next, and perhaps the most imposing feature of the intrusion is the core of breccia, in which angular and disorientated fragments, varying in size from small chips to blocks yards in extent, are either packed together or separated by thin zones of fine-grained material of felsitic aspect (Plate II). The chaotic nature is only partly diminished by a crude alignment of the more elongate fragments parallel to the long axis of the outcrop. Blocks of bedded crystalline limestone are overwhelmingly the most abundant constituent of the breccia, though there are a few scattered fragments of mica-schist, and various appinitic types; clearly only the adjacent country rocks are represented. The matrix intimately veins the bedding-planes of the enclosures and, in detail, the margins of the latter are often transitional with the matrix.

The outer breccia differs from the inner in having somewhat smaller fragments. The contact with the country rock is quite planar and sharp except at the western end of the intrusion where material can be seen to have been broken from the wall. In another place, where the breccia cuts a felsitic dyke, it becomes rich in pieces of that dyke. On the foreshore the breccia is contiguous with two thin sills of brecciated material, containing schist or limestone according to the nature of the host rock. The local origin of the breccia is thus confirmed, with the added probability that none of the blocks has moved more than a few dozen yards.

Changes in the mineral composition of the enclosed blocks are generally restricted to a surface layer which rarely exceeds an inch in thickness. Epidotic minerals, sphene, and calcite occur in fine grained aggregates which are closely associated with feldspathic veinlets (Text-fig. 2A). Where penetration is intense in this surface layer the limestone is entirely transformed; isolated veinlets are bounded by narrow zones of the new minerals and where veining is absent the calc-silicates are but sparsely developed. A very pale-green amphibole develops in the aggregates of epidotic minerals and increases in quantity in sympathy with the abundance of felsic veinlets. In the most altered zones the minerals form swirling patterns indicating a degree of mobilization. Sometimes a kind of micro-brecciation develops in which rectangular patches of calc-silicate minerals, with a little introduced quartz and feldspar, lie in a felsic base containing a few grains of epidote-clinozoisite. The pelitic material, consisting essentially of quartz and biotite, is seen in thin sections to have suffered a contact type of recrystallization, though the bedding and the orientation of the micas is often preserved; these original structures may be obscured by introduction



TEXT-FIG. 2.—Some aspects of the Matrix of the Breccia. A, the outer zone of calc-silicates around a limestone inclusion; B, the splitting of a plate of microcline by quartz-calcite veinlets; C, the breaking up of a sphene; D, the splitting of a plate of plagioclase; E, the more felsitic type of matrix, ground mass of hornblende, biotite, plagioclase, quartz and calcite. All on same scale. *h* = amphibole (also hatched in A), *b* = biotite, *c* = calcite, *e* = epidote-clinozoisite, *i* = pyrites, *m* = microcline, *p* = plagioclase, *q* = quartz, *s* = sphene.

of alkali feldspar and quartz. In the limit it would be impossible to distinguish between altered pelite and the fine-grained felsite. It is clear, therefore, that the disruption of the metasediments was accompanied by a thermal and additive metamorphism.

The material between the blocks is always continuous with the main felsite ring and is of very similar appearance in the field. It is variable in colour and hardness but is too fine-grained for the constituent minerals to be identified. Thin sections of the matrix (Text-fig. 2E) show precisely the same textures as the finer parts of the main felsite

though a new feature is the presence of coarse irregular areas of quartz and microcline which are presumably of slightly later crystallization. This microcline is penetrated by quartz-calcite veinlets—dilation by the latter is indicated by the disturbance of the twin-lamellae and cleavages of the feldspar (Text-fig. 2B). There is evidence of fracture of other minerals (Text-fig. 2D) and complete separation of the parts is shown by crystals of sphene (Text-fig. 2C). The thin slices reveal a very considerable range in composition from felsite with a few grains of calc-silicate minerals to a rock indistinguishable from the most altered parts of the xenoliths, so that it is often impossible to draw any hard and fast line between the mobilized metasomatic zones of the blocks and the matrix. Although much of the latter is composed of plagioclase laths, interstitial quartz, and intergrowths of these two minerals, it is never free from grains of epidotic minerals and especially of pale green amphibole. It seems therefore that at least part of the matrix is composed of the material derived from the enclosures, which has recrystallized together with new quartz and feldspar.

Conclusion and Discussion

In this intrusion country rocks have been shattered, fragmented, and mixed. Such a disruption, occurring within a steeply-walled and sharply-cut pipe, can best be attributed to gas-drilling. The fragments are, however, of local origin; they can be seen in the process of removal from the walls and there is none of the abrasion and consequent rounding which characterizes the far-travelled enclosures of the nearby Kilkenny intrusion-breccia (W. S. Pitcher and H. H. Read, 1952).

Some evidence for the presence of a gaseous fraction is provided by the vesicular nature of the main felsite, so that we are reminded of the emphasis placed by H. G. Smith (1946) on the association of a gas phase with the genesis of lamprophyric rocks. Further, the degree of metasomatism seems inconsistent with the small amount of presumably magmatic material introduced into the breccia, so that it seems necessary to invoke the superior chemical activity of hot gases. That such gases would be of a hydrous nature is suggested by the dominance of hydroxyl-bearing minerals; we can be certain of the presence of some carbon dioxide. D. L. Reynolds (1956) has drawn attention to a number of examples of quite intense metasomatism of fragments in intrusion-breccias and also to the efficacy of gases in promoting such reactions.

The felsitic matrix is clearly of complex origin, for it is variously loaded with derivatives of the country-rocks. Indeed it could be argued that this matrix was largely formed by the comminution, alteration, and recrystallization of metasedimentary material, perhaps by the passage of just such a reactive gas as envisaged above. Further, some of the crystal components of the felsitic rocks have been fractured,

disrupted, and probably corroded, at the time of emplacement; we recall the obvious splitting of microcline and the disruption of the sphenes. But it is difficult to demonstrate the extent of the fracturing process, for the proof of brecciation of single crystals, as distinct from corrosion, depends on the identification of the separated parts, and these may be widely scattered; certainly at the present level the *recognizable* proportion of such purely tuffisitic material is not large. Furthermore, this matrix is continuous with the main felsite which has some of the features normally associated with rocks solidified from magmas: finer-grained margins with well-formed phenocrysts and a texture of interlocking laths within the groundmass of the coarser types. In fact we have no reason to believe that crystals formed from a magma, intruded along with a gas phase, would escape the effects suffered by country rock incorporated in the intrusion. We therefore provisionally conclude that we are dealing with the shattering, partial permeation, and recrystallization produced by a gas, or gas-charged tenuous medium, moving with, and in the van of, a magmatic intrusion.

The time relationship of this intrusion-breccia is most important. It is associated with a suite of lamprophyres and felsites which span the time of emplacement of the Ardara granodioritic pluton. Other intrusion-breccias occur in this association, varying in size and in the composition of the matrix. We have already mentioned one of these, the Kilkenny intrusion, which has both an appinitic and granophyric base. Slightly further afield G. P. L. Walker and G. P. Leedal (1957, p. 229) describe a remarkable breccia, cutting the Barnsmore granite, from which radiates a swarm of dykes with lamprophyric affinities.

We have, therefore, an association involving a granodiorite-tonalite pluton and various appinites, hornblende lamprophyres, felsites, and intrusion breccias the details of which are being worked out. Surely the most intriguing part of this association is the link between gas-drilled, tuffisitic pipes and post-tectonic plutons.

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EXPLANATION OF PLATE II

The breccia core of the Dunmore Intrusion, looking south.

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BRECCIA CORE OF THE DUNMORE INTRUSION.

Differing Powers of Crystal Nucleation as a Factor Producing Diversity in Layered Igneous Intrusions

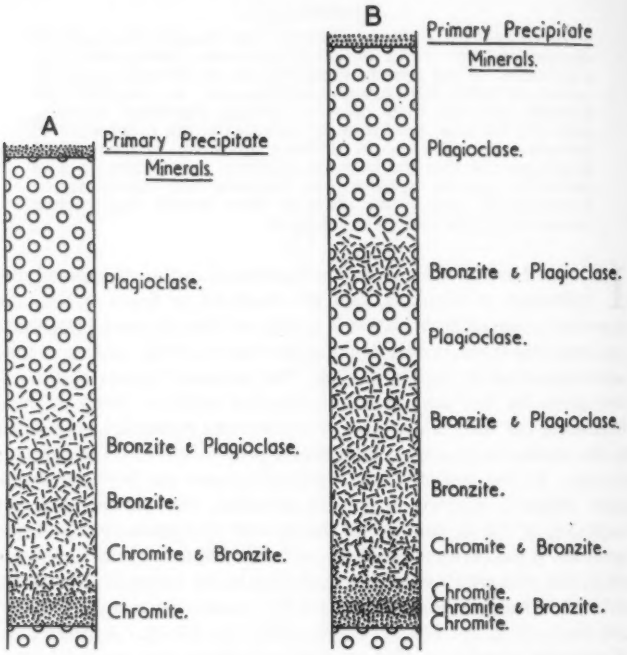
By L. R. WAGER

ABSTRACT

To account for a type of rhythmic unit found in the Bushveld complex of South Africa and probably in other layered intrusions, a hypothesis is put forward dependent on the different powers of crystal nucleation from supersaturated magma. It is suggested, for example, that the three common primary precipitate minerals, chromite, bronzite, and bytownite nucleated in this order which is probably dependent on the differing complexity of their crystal structures and that the common rhythmic unit, beginning with chromitite, passing upwards into bronzitite and ending with a bytownite-rich rock is the result of these crystals accumulating successively at the bottom of the liquid.

IN layered intrusions such as the Skaergaard in East Greenland, the Stillwater in Montana, and the Bushveld in South Africa, the dominant cause of the variation is usually ascribed to crystal fractionation resulting from crystals falling to the bottom of the magma as they were successively formed by cooling. This process of bottom accumulation gives the less obvious cryptic layering which is found in these intrusions, but there is also a more conspicuous rhythmic layering due to the successive layers having different proportions of the separating crystals. In the case of the Skaergaard intrusion much of the small-scale rhythmic layering is gravity stratified, the heavier minerals occurring at the bottom of the band, with progressively less dense upwards. It has been suggested that such banding is due to a winnowing effect, like that which separates chaff from grain, acting on crystals of different densities during movement by convection currents (Wager and Deer, 1939, pp. 272–3; Wager, 1953, pp. 347–8). Another type of variation, usually on a bigger scale as in Rhum and in much of the Bushveld complex, may have another origin. In Rhum, as Brown has shown (1956), there are units a hundred or so feet thick consisting of olivine-rich layers in the lower part (peridotite) passing gradually into feldspar-rich layers in the upper (allivalite). This variation suggests that olivine was crystallizing as a primary precipitate mineral during the first part of the rhythmic unit and plagioclase, often accompanied by augite, during the later part. To account for this sequence Brown suggested successive pulses of basaltic magma of a critical composition such that, on slight cooling, olivine and chromite separated as stable phases and settled out, followed after a small cooling interval by feldspar and sometimes by augite. A process of this kind involving a series of pulses of magma requires successive removal of the residual magmas by some means which Brown considered might well be

extrusion from a volcanic vent. This kind of hypothesis, which seems necessary for Rhum because of the lack of cryptic variation in 2,600 feet of the layered series, requires a critical magma composition and a repetition of a rather elaborate sequence of events, namely injection



TEXT-FIG. 1 (A).—Diagrammatic representation of a simple rhythmic unit in the critical zone of the Bushveld—thickness of a unit of the order of 100 feet.
(B).—Common type of complex rhythmic unit.

of magma, cooling through a certain temperature range, and extrusion of some residual magma.

An alternative hypothesis dependent on different powers of crystal nucleation has for some time seemed to me a possibility for some of the rhythmic variation in Rhum, and during a recent visit to South Africa, it has appeared that one type of variation found in the Bushveld intrusion may also be due to the same process. In the lower part of the Bushveld there is a rhythmic unit, often repeated, beginning with chromitite which passes into a dominantly bronzite rock which, in

turn, passes into a bronzite-plagioclase rock and ends as a dominantly plagioclase rock (Text-fig. 1A). The unit is often complicated by minor fresh starts or returns to an earlier phase as illustrated by Text-fig. 1B. Other units of this general type, although with some different primary precipitate crystal phases, occur around the Merensky reef horizon and in the gabbros of the main zone especially at the horizon of the magnetite bands at the top. In the new hypothesis the order of crystallization of the primary precipitate minerals in the rhythmic units is considered to be due to their respective powers of nucleation from a somewhat supercooled magma, rather than the result of external influences such as successive pulses of magma. The loss of heat from the intrusion is assumed to be steady and supersaturation, with metastable conditions is considered to alternate with equilibrium conditions.

The hypothesis involving different powers of crystal nucleation may be most simply illustrated by the rhythmic units at the chrome horizon in the Bushveld (Text-fig. 1). Three primary precipitate minerals are involved—chromite, bronzite, and basic plagioclase. All three minerals were stable and available over a long period during which thicknesses of about a kilometre of layered rocks were formed in some places. The minerals, however, accumulated in different proportions in a rhythmic way, giving the variation just described. To explain the effects of different powers of nucleation let it be considered that cooling is slow and that all the crystals formed in the preceding period have sunk to the bottom, leaving a clear liquid above. With continued cooling some supersaturation will occur before crystal nuclei can again develop in the liquid. Although chromite, bronzite, and plagioclase should all be separating from the liquid if equilibrium conditions existed, one of these crystal phases may well nucleate more easily than the others from the supersaturated liquid. It is likely that the crystals of simple structure such as the spinels would nucleate before those of complex structure, like the feldspars. There is some experimental evidence obtained long ago by Doelter and others on the ease of nucleation (cf. Eitel, 1954, pp. 569–77). Furthermore the general experience of those who investigate silicate systems experimentally is that magnetite and olivine usually crystallized easily while more complex silicates do not. A theoretical discussion of the probable ease of crystallization of various minerals has also been presented by Goldsmith (1953). In the special case here considered it is believed that chromite, the mineral of simplest structure, first formed crystal nuclei throughout a considerable thickness of liquid and that the crystals grew rapidly, reducing the supersaturation and raising the temperature towards, or to the equilibrium value. The crystals formed would tend to sink out of the liquid and so produce the first part of a rhythmic unit. On further cooling another crystal phase would sooner or later appear in the supersaturated

liquid; in the special case considered it would probably be bronzite, the primary precipitate mineral of the next most simple structure. The bronzite would crystallize in considerable quantities as its component elements are abundant in the magma, and the crystals would sink to form the next part of the rhythmic unit. Finally, supersaturation for feldspar would reach a point when spontaneous nucleation of this crystal phase would also occur and feldspar would precipitate. At this stage it is suggested that all the crystals were removed from a layer of the liquid by sinking. On further cooling, the liquid would pass into the supersaturated state and there would be a pause in precipitation; then the cycle would begin over again by precipitation of the mineral with the greatest power of crystal nucleation.

The small and local temperature changes resulting from a process of supersaturation and spontaneous nucleation are no doubt complicated. Growth of the crystals from the slightly supersaturated liquid will tend to raise the temperature to the equilibrium value. In the case of chromite which is formed in relatively small quantities, the amount crystallized may not be sufficient to do this, but certainly by the end of the process, when all the phases are separating, the temperature will be raised to the equilibrium value. The separation of the first crystal phase will no doubt shift slightly the equilibrium condition for the still un-nucleated phases because the composition of the liquid will be slightly changed. The effect to be anticipated is a slight increase in the degree of supersaturation of the other constituents and thus nucleation of the other phases should be encouraged. These details are interesting and perhaps important but they should not greatly affect the overall sequence of events suggested as the cause of this type of layering.

Another factor probably having an important effect on the local conditions in the magma is movement of the liquid due to convection currents. In thick layered intrusions loss of heat through the bottom or sides cannot be the main way of cooling. Instead the heat loss must be mainly from the top surface, resulting in convection, at any rate in the less viscous basic magmas. Convection currents in some layered intrusions may not be vigorous enough to produce sorting by a winnowing of the sinking crystals, as in the Skaergaard intrusion, but they may well produce a patchy distribution of temperature, causing irregularities in crystal nucleation and, as a consequence, variations in the proportions in the mineral accumulate. The suggested nucleation sequence to account for the rhythmic units in the critical zone of the Bushveld intrusion, may have taken place, for instance, in thick layers of stationary magma or in smaller convecting patches of liquid resembling drifting clouds.

The hypothesis of variations in the sequence of events due to different powers of nucleation combined with irregularities in cooling resulting

from convection, leads to an explanation of the variety in the crystal accumulates of layered intrusions without postulating processes external to the magma pool. In this respect it is similar to the hypothesis of crystal winnowing which was suggested for certain small-scale units of rhythmic layering in the Skaergaard intrusion, many of which show gravity stratification. However, in the Skaergaard intrusion difficulties have arisen in explaining the mineral assemblages solely on a specific gravity and winnowing basis and it is probable that differences in the power of crystal nucleation also played a part; in particular this factor may be responsible for the large scale " Triple Band " layering of the Skaergaard intrusion. In some layered intrusions, external influences may be superimposed on the internal processes, as for instance, successive pulses of magma injection. At least a second injection of magma seems to be indicated for the Bushveld complex by the careful mineralogical work of Lombaard (1934) and his students. Successive injection of magma may well be a factor in the variation found in Rhum, and it may well be a factor in the development of the impressive rhythmic units of the Great Dyke of Southern Rhodesia (cf. Worst, 1956). When dealing with the early rhythmic units of layered intrusions like the chromite-bronzite-bytownite unit of the Bushveld complex, successive injections of an early, high-temperature magma could account for the repetition of the units. However, an essentially similar type of unit, occurring at high levels in the Bushveld and having magnetite, iron-rich rhombic pyroxene, and andesine as the primary phases, cannot be so convincingly explained in this way. The compositions of the phases are appropriate to the stage reached in the cryptic variation. If produced by a new pulse of magma then its composition would have to be exactly similar to that which had already resulted from the cryptic variation occurring up to this stage. This is an unlikely coincidence and suggests that the higher rhythmic units of this kind in the Bushveld are not due to further injection of magma from external sources.

Rhythmic layering as defined in the Skaergaard paper, that is, variation due to differences in the proportions of the primary crystal phases, should probably be divided into two types: one, which is usually on a small scale due to a winnowing effect, the other, which may be on a small or large scale, due to differing powers of crystal nucleation. The powers of nucleation of the different mineral species involved in layered intrusions should be investigated experimentally to decide whether or not the order is the one suggested by the known types of rhythmic units.

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A Note on the Crag in Norfolk

By R. A. Downing *

Abstract

In East Norfolk, boreholes have revealed the presence of a northern and a southern clay bed in the Crag. These lie at different horizons and have been linked to clay exposures previously correlated with the Chillesford Beds of Suffolk. It is concluded that a clay facies is developed at two main horizons in the Crag in Norfolk.

THE Crag is the general name applied to the false-bedded and frequently shelly sands, and thin clays overlying the Chalk and Eocene in East Anglia. With the exception of the Coralline Crag, they are now classified as Pleistocene. In Norfolk, three divisions have been reported, namely :—

Weybourne Crag
Chillesford Clay
Norwich Crag

In the Norwich area and the Bure Valley, the total thickness of the Crag, as proved at outcrop, is about 30 feet. Evidence from borings shows that the thickness increases towards the east, coinciding with an increase in the easterly slope of the Chalk surface. In addition to the general easterly thickening, it exceeds 100 feet in two synclinal downwarps which trend north-east from South Burlingham towards Winterton and from Thwaite St. Mary towards Great Yarmouth respectively (see Text-fig. 2). Near Winterton the thickness is probably greater than 200 feet.

Earlier workers have been unable to correlate convincingly many exposures of the Crag with the Norwich and Weybourne crags, owing to lack of sufficient fossiliferous exposures. At outcrop, the Norwich and Weybourne crags rest directly on the Chalk, but in East Norfolk the Norwich Crag overlies the Eocene (Text-fig. 1).

The Norwich Crag is known to occur in the Bure Valley and areas to the south, while the Weybourne Crag is exposed on the north Norfolk coast. Pebbly sands and gravels containing *Macoma balthica* (a characteristic fossil of the Weybourne Crag) have also been found at Belaugh, Wroxham, and Crostwick (all in the Bure Valley) and near Honing.

Clay exposures occurring in Crag deposits in the Bure and Yare valleys were mapped by Geological Survey officers (Woodward, 1881), and C. Reid (1890, p. 136) considered them to be equivalent to the

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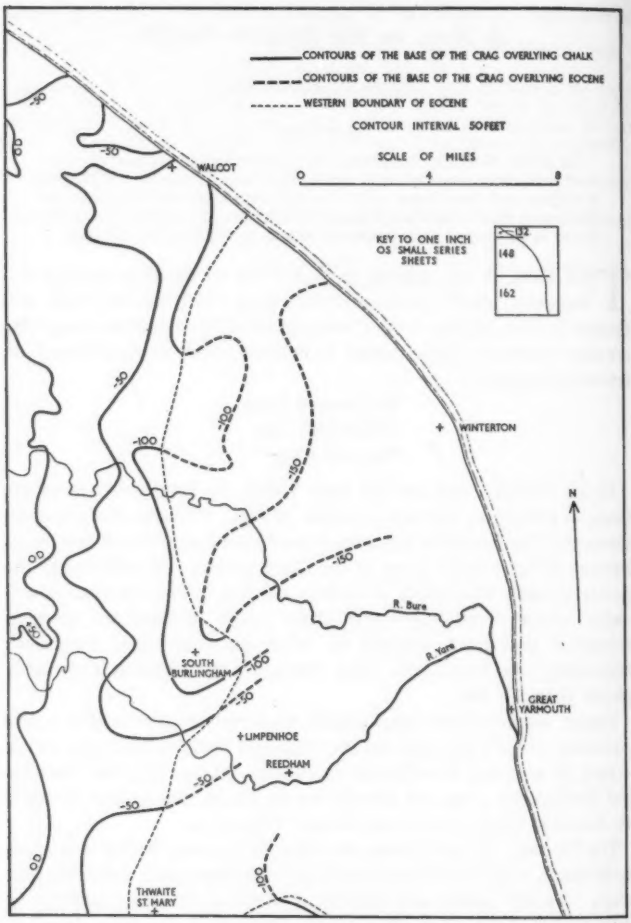
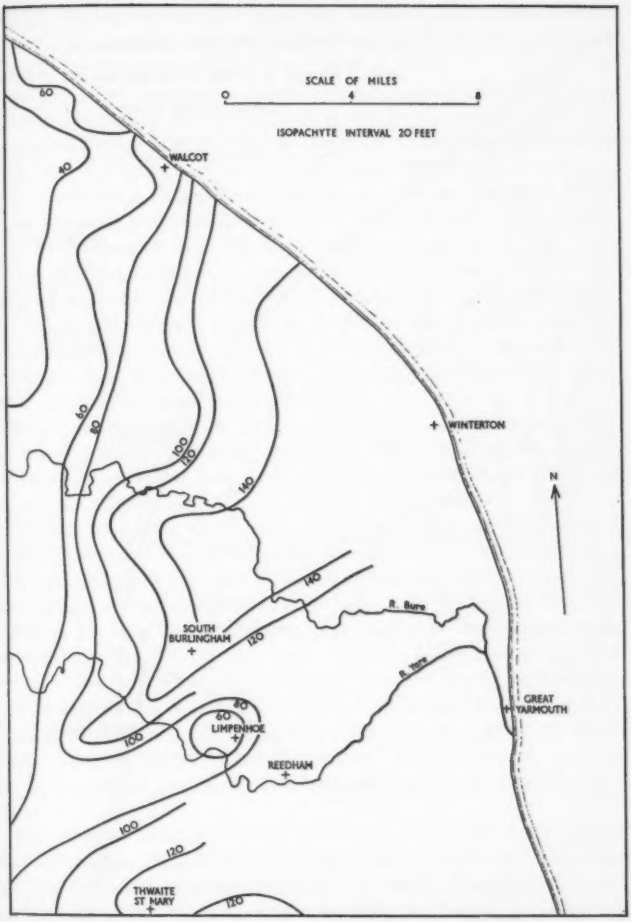


TEXT-FIG. 1.—Contours of the base of the Crag.

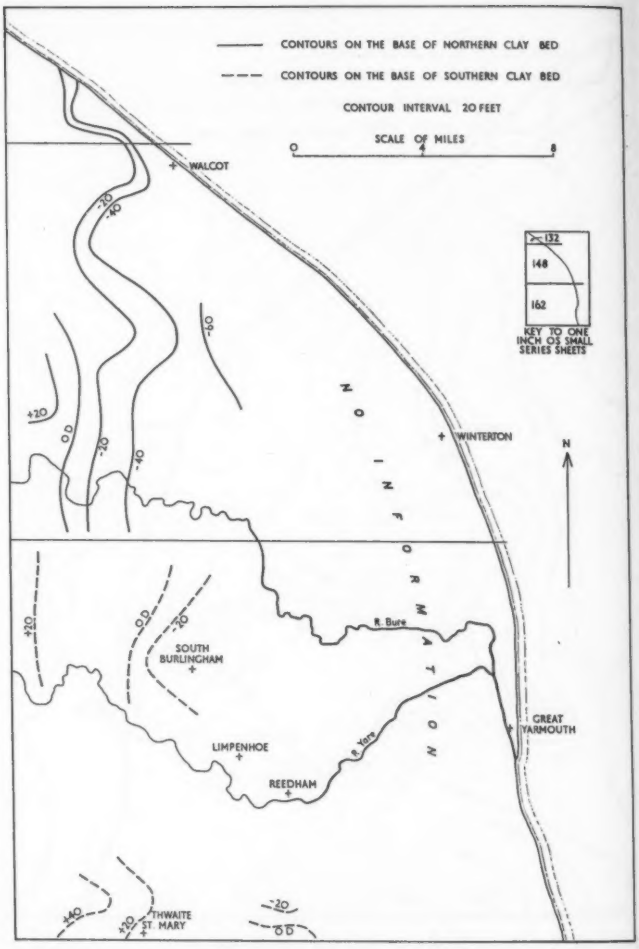
Chillesford Clay. The Chillesford Beds, however, were named from their typical development at Chillesford in Suffolk where they rest either on Red or on Norwich Crag, and are composed of fine micaceous sands overlain by micaceous clay. According to Harmer (1896, p. 770) the clay is an estuarine deposit which formed in a channel of the



TEXT-FIG. 2.—Generalized map showing isopachytes of the Crag (thicknesses in the Yare and Bure valleys are actually less than those shown on the map due to erosion).

Pleistocene River Rhine. He suggested that the sinuous pattern obtained by joining the exposures of the bed, marked the course of this channel.

From his mapping in the Norwich area, H. B. Woodward (1881,



TEXT-FIG. 3.—Contours on the base of clay beds in the Crag.

p. 34) was unconvinced that these Norfolk clays were confined to a single horizon, though he admitted that, in some sections, two or more bands of clay might be seen to resemble the Chillesford Clay on lithological grounds.

Nevertheless the succession (1) Norwich Crag, (2) Chillesford Clay,

and (3) Weybourne Crag is frequently quoted despite views to the contrary, for example that the Chillesford Clay might be equivalent in age to the Weybourne Crag (Reid, 1890, p. 131).

Evidence recently obtained from an examination of over 300 records of boreholes drilled in Norfolk, which are in the possession of the Geological Survey, has revealed the presence of thin clay beds in the Crag, two of which cover considerable areas. One of these two clay beds occurs in the area covered by Ordnance Survey One Inch Small Series Sheets 132 (Mundesley) and 148 (North Walsham), see Text-fig. 3, and is from 10 to 15 feet thick, dipping slightly to the east. The second bed, which is not so persistent, is usually from 5 to 10 feet thick. It lies in the area of the Great Yarmouth Sheet (162) apparently at a higher and different horizon from that of the northern bed. The discrepancy in level cannot be explained structurally as the underlying Chalk is undisturbed and it appears, therefore, as if the two clay beds are at different horizons within the Crag.

Both these clay beds are absent locally and towards the west they become impersistent and pass into a sandy shelly facies. Their eastern boundary is uncertain due to lack of information, but there is no evidence to suggest that they die out towards the east.

The clay exposures in the Bure and Yare valleys (except for those at Limpenhoe and Reedham) which have previously been correlated with the Chillesford Clay can be linked to one or other of the two clay beds identified from borehole records. The Limpenhoe and Reedham outcrops, however, are probably slightly higher in the sequence than the southern clay. These clay beds appear to be developed near the top of the Norwich Crag for, although it is difficult in borehole records to differentiate the Upper Pleistocene from the Crag because of their lithological similarity, the clays are considered to be overlain by sands of the Crag. The variations in thickness of the Crag as a whole are due to variations in the thickness of the deposits below the clay beds.

The evidence presented above confirms H. B. Woodward's opinion that Pleistocene clays which have been claimed to be of Chillesford age, do not occur as one continuous clay bed in Norfolk. It seems rather that a clay facies is developed near the top of the Norwich Crag at two main horizons. There is no evidence that these clays were deposited in a channel as Harmer suggested, it appearing more probable that they are of estuarine origin, the estuary extending over East Norfolk.

The author wishes to thank his colleagues of the Geological Survey and Museum for help and advice received in the preparation of this note.

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CORRESPONDENCE

AGE OF THE CRETACEOUS BASAL CONGLOMERATE AT MURLOUGH BAY, Co. ANTRIM

SIR,—The Cretaceous basal conglomerate seen in the coastal area between Ballycastle and Cushendun, in the north-eastern corner of Co. Antrim, is of doubtful zonal position owing to its lack of diagnostic contents. At first sight, it seems to be simply a basal facies of the succeeding Chalk, or white Limestone, of *B. mucronata* age. This, however, is not the case. As typically developed it does not contain *B. mucronata*, and its junction with the chalk above is distinctly disconformable. Nor, apparently, does *Gonioteuthis* occur; yet this belemnite is common in the upper part of the pre-*B. mucronata* White Limestone developed at Whitepark Bay, eleven miles to the west of Murlough Bay at the north-western end of the coastal conglomerate outcrop. Thus the conglomerate appears to be older than the *G. quadrata* age assumed by Hume (1897), and to be separated from the succeeding White Limestone by a non-sequence covering one to several zones. On the other hand, the find by the Geological Survey (Anderson, 1957) of a *Lewesiceras* cf. *sharpei* Spath in the conglomerate at Torr Head shows that this cannot be older than Turonian.

In a recent discussion (Reid, 1958) of the Upper Cretaceous Hexactinellida of Co. Antrim and their bearing on stratigraphical problems, I suggested that the basal conglomerate of this district may pass laterally southwards into the glauconitic chalk with sponges developed south of Carnlough to the Larne–Islandmagee area. This is again a problematical deposit. It is evidently Senonian in age, but lacks distinctive marker fossils; the only belemnite present is *Actinocamax verus* Miller, which occurs at Whitepark Bay in the flintless *Marsupites* chalk. The upward junction with White Limestone with *B. mucronata* is thus again evidently disconformable, though no marked lithological break is apparent. This glauconitic chalk is typically rich in phosphatised remains of hexactinellid sponges, occurring particularly in a dense concentration which is roughly coincident with the upward passage in this area from glauconitic sandstone into glauconitic chalk, and some distance below the limiting disconformity; the main sponge band may be roughly one foot thick, and followed by a similar or rather greater thickness of hard, less glauconitic chalk with fewer sponges. My suggestion that this facies passes laterally into basal conglomerate of similar age was based on discovery of typical sponge bed Hexactinellida in a pebbly glauconitic chalk seen in slipped blocks at Red Bay, east of Glenariff, between the areas where the two main types are exposed.

Hume's assessment of the fauna in general (1897, p. 568, tab. 1) makes the glauconitic chalk with sponges of *Marsupites* age, in the wide sense including the zones of *Uintacrinus* and *Marsupites* s.s.; a similar view has recently been expressed by McGugan (1957), who has studied the problem in conjunction with Dr. J. M. Hancock. Study of the sponges again supports this view, but leads to an additional suggestion. Sponges have generally been regarded as of

little stratigraphical importance; my own studies (1958) of the Hexactinellida of the Chalk of England show, instead, a definite sucession of faunas. Judged by comparison, the sponge bed fauna has no distinctly Turonian elements. Many of its traceable species are forms which seem first to occur in England in the zone of *M. cor-anguinum*; there are, however, species of several genera which are typical of the higher Senonian, such as *Coeloptychium* Goldfuss and *Lepidospongia* F. A. Roemer. Further, the glauconitic chalk above the main sponge band—and sometimes the sponge band itself, which seems to be slightly diachronous—yields several species which are otherwise typical of the *I. lingua* sponge beds of S.E. Yorkshire. There is thus a suggestion that parts of this glauconitic chalk are of *O. pilula* age: that is, slightly younger than the authors cited suggest.

When these suggestions based on sponges were made, I had not obtained any determinable examples from the conglomerate of N.E. Antrim. Its outcrop at Murlough Bay has now yielded two specimens of *Rhizopoterion cribrosum* (Phillips). This is a species recorded in England by Rowe (1900, p. 360, as *Ventriculites cribrosus*) from as low as the *I. labiatus* zone. My own collecting indicates, however, that lower Senonian and earlier records refer properly to distinct, though partly congeneric, forms; the true *R. cribrosum* seems only to occur from the zone of *Marsupites* upward, and mainly above it. Its Irish distribution is similar. The species is common in the glauconitic chalk of eastern Antrim, either in the part above the main sponge band, or sometimes in the sponge band itself where this contains supposed *I. lingua* elements. It is present also in the higher glauconitic chalk and mulatto of the Belfast area, of *O. pilula* and *G. quadrata* age, and in various localities in the typical White Limestone of the *B. mucronata* zone. Its local range is thus mainly upper Senonian, and its earliest occurrence at a level which is possibly as high as the zone of *O. pilula*.

The occurrence of this sponge at Murlough Bay thus suggests that part at least of the conglomerates is of middle or upper Senonian age, no older than the glauconitic chalk in which *R. cribrosum* occurs to the south, and distinctly younger than the maximum age suggested by the Torr Head *Lewesiceras*.

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AFRICAN EROSION SURFACES

SIR,—In a recent letter to the *Geological Magazine*, Pallister (1958) has referred to a spirited controversy on the origin of certain erosion surfaces in north-east Belgian Congo between Lepersonne (1949, 1956*a*, 1956*b*, 1958) and the writer (1954*a*, 1954*b*, 1956, 1958). During the course of the controversy, I (1958, pp. 369–370) referred to a paper by Pallister (1956) in which

he showed the probable correlation of a bevel in the Masaka District of Uganda known as the Koki Surface with the Buganda Erosion Surface (mid-Tertiary). Controversy, in turn, had developed on the correlation of the Koki Surface (McConnell, 1955, 1957; Pallister, 1956).

In the statement that Pallister quoted from my latest paper on African erosion surfaces (1958, p. 378), I may have read more into Pallister's work than was warranted. However, I was referring to the problem of the Koki Surface and its correlation, which I had detailed in a preceding part of the paper (1958, pp. 369–370). This reference was made to show that Lepersonne's (1956*b*) correlation of an " aplanissement fin-Crétacé PI (Congo belge) " with the Koki Surface of Uganda was questionable. In the statement that Pallister quoted, unfortunatley I did not clarify the issue, and I assume the responsibility for not doing so.

Pallister's calling attention to this matter is appreciated, and I take the opportunity to correct the record.

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